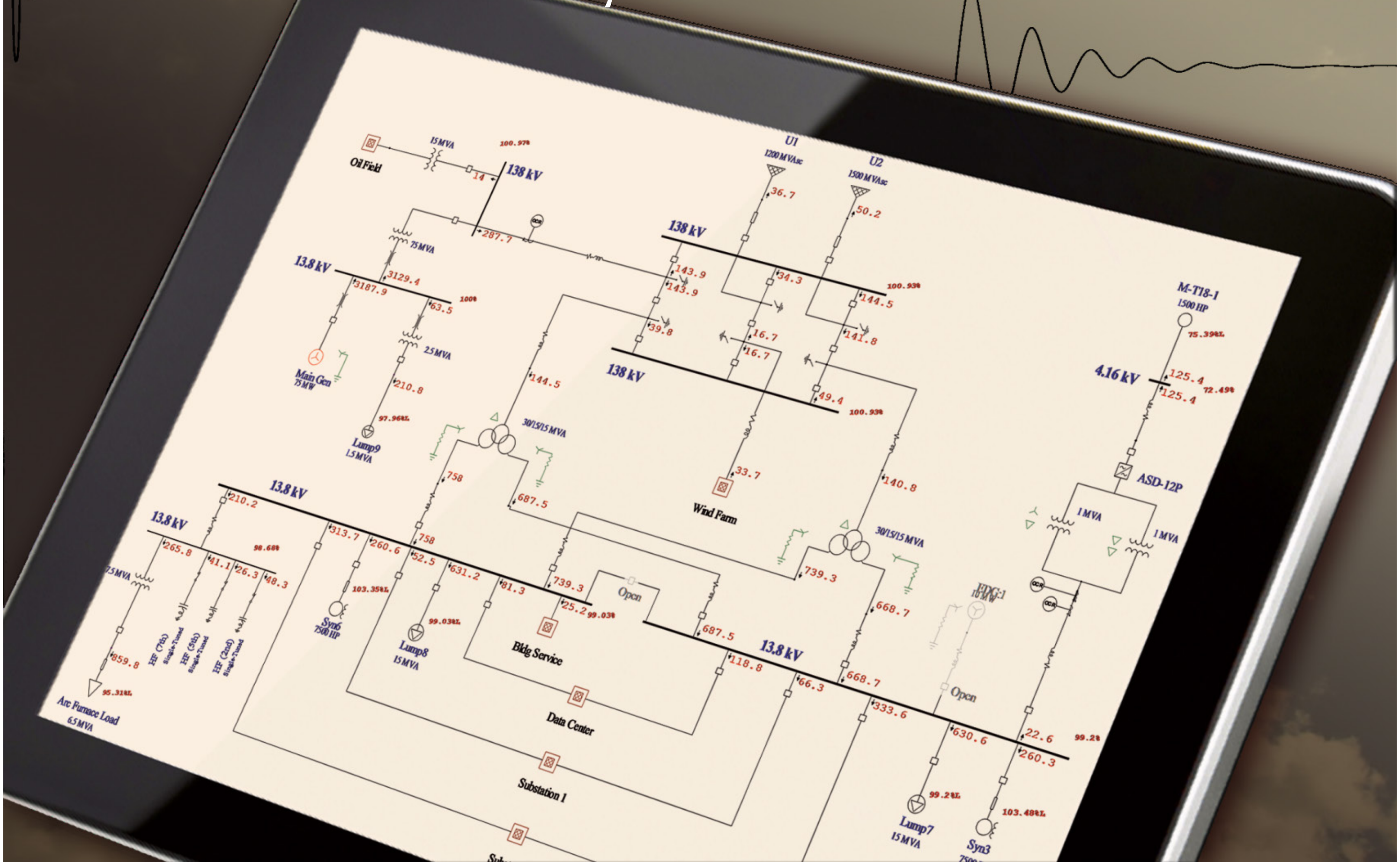
IEEE 3000 STANDARDS COLLECTION®

IEEE 3002 STANDARDS:
POWER SYSTEMS ANALYSIS

IEEE Std 3002.7™-2018

Recommended Practice for Conducting Motor-Starting Studies and Analysis of Industrial and Commercial Power Systems



IEEE STANDARDS ASSOCIATION

IEEE

IEEE Recommended Practice for Conducting Motor-Starting Studies and Analysis of Industrial and Commercial Power Systems

Sponsor

Technical Books Coordinating Committee
of the
IEEE Industrial Applications Society (IAS)

Approved 5 September 2018

IEEE-SA Standards Board

Abstract: Activities related to motor-starting studies, including design considerations for new systems, analytical studies for existing systems, as well as operational and model-validation considerations for industrial and commercial power systems are described. Motor-starting analysis includes evaluation of motor-starting current and voltage drop. Accuracy of calculation results primarily relies on system modeling assumptions and methods used. The use of computer-aided analysis software, with a list of desirable capabilities recommended to conduct a modern motor-starting study, is emphasized. Examples of system data requirements and result-analysis techniques are presented. Benefits obtained from motor-starting studies are discussed, and various types of computer-aided motor-starting studies are examined. Data or information required for these studies, as well as the expected results of a motor-starting study effort, are also reviewed.

Keywords: adjustable speed drive, dynamic motor starting, IEEE 3002.7, motor acceleration, motor protection, motor reacceleration, motor starting, reduced-voltage starters, soft-starters, static motor starting, variable frequency drive, voltage flicker

---

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

PDF: ISBN 978-1-5044-5341-7 STD23433
Print: ISBN 978-1-5044-5342-4 STDPD23433

Important Notices and Disclaimers Concerning IEEE Standards Documents

IEEE documents are made available for use subject to important notices and legal disclaimers. These notices and disclaimers, or a reference to this page, appear in all standards and may be found under the heading "Important Notices and Disclaimers Concerning IEEE Standards Documents." They can also be obtained on request from IEEE or viewed at http://standards.ieee.org/IPR/disclaimers.html.

Notice and Disclaimer of Liability Concerning the Use of IEEE Standards Documents

IEEE Standards documents (standards, recommended practices, and guides), both full-use and trial-use, are developed within IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Association ("IEEE-SA") Standards Board. IEEE ("the Institute") develops its standards through a consensus development process, approved by the American National Standards Institute ("ANSI"), which brings together volunteers representing varied viewpoints and interests to achieve the final product. Volunteers are not necessarily members of the Institute and participate without compensation from IEEE. While IEEE administers the process and establishes rules to promote fairness in the consensus development process, IEEE does not independently evaluate, test, or verify the accuracy of any of the information or the soundness of any judgments contained in its standards.

IEEE does not warrant or represent the accuracy or content of the material contained in its standards, and expressly disclaims all warranties (express, implied and statutory) not included in this or any other document relating to the standard, including, but not limited to, the warranties of: merchantability; fitness for a particular purpose; non-infringement; and quality, accuracy, effectiveness, currency, or completeness of material. In addition, IEEE disclaims any and all conditions relating to: results; and workmanlike effort. IEEE standards documents are supplied "AS IS" and "WITH ALL FAULTS."

Use of an IEEE standard is wholly voluntary. The existence of an IEEE standard does not imply that there are no other ways to produce, test, measure, purchase, market, or provide other goods and services related to the scope of the IEEE standard. Furthermore, the viewpoint expressed at the time a standard is approved and issued is subject to change brought about through developments in the state of the art and comments received from users of the standard.

In publishing and making its standards available, IEEE is not suggesting or rendering professional or other services for, or on behalf of, any person or entity nor is IEEE undertaking to perform any duty owed by any other person or entity to another. Any person utilizing any IEEE Standards document, should rely upon his or her own independent judgment in the exercise of reasonable care in any given circumstances or, as appropriate, seek the advice of a competent professional in determining the appropriateness of a given IEEE standard.

IN NO EVENT SHALL IEEE BE LIABLE FOR ANY DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR CONSEQUENTIAL DAMAGES (INCLUDING, BUT NOT LIMITED TO: PROCUREMENT OF SUBSTITUTE GOODS OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR BUSINESS INTERRUPTION) HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE PUBLICATION, USE OF, OR RELIANCE UPON ANY STANDARD, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE AND REGARDLESS OF WHETHER SUCH DAMAGE WAS FORESEEABLE.

Translations

The IEEE consensus development process involves the review of documents in English only. In the event that an IEEE standard is translated, only the English version published by IEEE should be considered the approved IEEE standard.

Official statements

A statement, written or oral, that is not processed in accordance with the IEEE-SA Standards Board Operations Manual shall not be considered or inferred to be the official position of IEEE or any of its committees and shall not be considered to be, or be relied upon as, a formal position of IEEE. At lectures, symposia, seminars, or educational courses, an individual presenting information on IEEE standards shall make it clear that his or her views should be considered the personal views of that individual rather than the formal position of IEEE.

Comments on standards

Comments for revision of IEEE Standards documents are welcome from any interested party, regardless of membership affiliation with IEEE. However, IEEE does not provide consulting information or advice pertaining to IEEE Standards documents. Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments. Since IEEE standards represent a consensus of concerned interests, it is important that any responses to comments and questions also receive the concurrence of a balance of interests. For this reason, IEEE and the members of its societies and Standards Coordinating Committees are not able to provide an instant response to comments or questions except in those cases where the matter has previously been addressed. For the same reason, IEEE does not respond to interpretation requests. Any person who would like to participate in revisions to an IEEE standard is welcome to join the relevant IEEE working group.

Comments on standards should be submitted to the following address:

Secretary, IEEE-SA Standards Board
445 Hoes Lane
Piscataway, NJ 08854 USA

Laws and regulations

Users of IEEE Standards documents should consult all applicable laws and regulations. Compliance with the provisions of any IEEE Standards document does not imply compliance to any applicable regulatory requirements. Implementers of the standard are responsible for observing or referring to the applicable regulatory requirements. IEEE does not, by the publication of its standards, intend to urge action that is not in compliance with applicable laws, and these documents may not be construed as doing so.

Copyrights

IEEE draft and approved standards are copyrighted by IEEE under U.S. and international copyright laws. They are made available by IEEE and are adopted for a wide variety of both public and private uses. These include both use, by reference, in laws and regulations, and use in private self-regulation, standardization, and the promotion of engineering practices and methods. By making these documents available for use and adoption by public authorities and private users, IEEE does not waive any rights in copyright to the documents.

Photocopies

Subject to payment of the appropriate fee, IEEE will grant users a limited, non-exclusive license to photocopy portions of any individual standard for company or organizational internal use or individual, non-commercial use only. To arrange for payment of licensing fees, please contact Copyright Clearance Center, Customer Service, 222 Rosewood Drive, Danvers, MA 01923 USA; +1 978 750 8400. Permission to photocopy portions of any individual standard for educational classroom use can also be obtained through the Copyright Clearance Center.

Updating of IEEE Standards documents

Users of IEEE Standards documents should be aware that these documents may be superseded at any time by the issuance of new editions or may be amended from time to time through the issuance of amendments, corrigenda, or errata. An official IEEE document at any point in time consists of the current edition of the document together with any amendments, corrigenda, or errata then in effect.

Every IEEE standard is subjected to review at least every ten years. When a document is more than ten years old and has not undergone a revision process, it is reasonable to conclude that its contents, although still of some value, do not wholly reflect the present state of the art. Users are cautioned to check to determine that they have the latest edition of any IEEE standard.

In order to determine whether a given document is the current edition and whether it has been amended through the issuance of amendments, corrigenda, or errata, visit the IEEE-SA Website at http://ieeexplore.ieee.org/ or contact IEEE at the address listed previously. For more information about the IEEE-SA or IEEE's standards development process, visit the IEEE-SA Website at http://standards.ieee.org.

Errata

Errata, if any, for all IEEE standards can be accessed on the IEEE-SA Website at the following URL: http://standards.ieee.org/findstds/errata/index.html. Users are encouraged to check this URL for errata periodically.

Patents

Attention is called to the possibility that implementation of this standard may require use of subject matter covered by patent rights. By publication of this standard, no position is taken by the IEEE with respect to the existence or validity of any patent rights in connection therewith. If a patent holder or patent applicant has filed a statement of assurance via an Accepted Letter of Assurance, then the statement is listed on the IEEE-SA Website at http://standards.ieee.org/about/sasb/patcom/patents.html. Letters of Assurance may indicate whether the Submitter is willing or unwilling to grant licenses under patent rights without compensation or under reasonable rates, with reasonable terms and conditions that are demonstrably free of any unfair discrimination to applicants desiring to obtain such licenses.

Essential Patent Claims may exist for which a Letter of Assurance has not been received. The IEEE is not responsible for identifying Essential Patent Claims for which a license may be required, for conducting inquiries into the legal validity or scope of Patents Claims, or determining whether any licensing terms or conditions provided in connection with submission of a Letter of Assurance, if any, or in any licensing agreements are reasonable or non-discriminatory. Users of this standard are expressly advised that determination of the validity of any patent rights, and the risk of infringement of such rights, is entirely their own responsibility. Further information may be obtained from the IEEE Standards Association.

Participants

At the time this IEEE recommended practice was completed, the Power Systems Analysis Working Group (IEEE 3002 Series) was chaired by **Farrokh Shokooh** with the following membership for the 3002.7 Working Group, motor-starting studies and analysis:

Tanuj Khandelwal, *Co-Chair*

Farrokh Shokooh, *Co-Chair*

Paul Cardinal
Jianjun Guo
Jun Qiu
Zia Salami
Aparna Sinha

The following members of the individual balloting committee voted on this recommended practice. Balloters may have voted for approval, disapproval, or abstention.

Ali Al Awazi
Mohammed Ashraf Ali
Saleman Alibhay
Thomas Barnes
G. Bartok
Michael Basler
Michael Bayer
Robert Beavers
Sirak Belayneh
Thomas Bishop
William Bloethe
Mark Bowman
Frederick Brockhurst
Gustavo Brunello
Nissen Burstein
William Byrd
Paul Cardinal
Kurt Clemente
Randall Cunico
Edson Da Costa Bortoni
Roger Daugherty
Glenn Davis
Matthew Davis
Davide De Luca
Gary Donner
Neal Dowling
Donald Dunn
Robert Durham
Carl Fredericks
Dale Fredrickson
Rafael Garcia
Carlos Gaytan
Mietek Glinkowski
Jalal Gohari
J. Travis Griffith
Randall Groves
Ajit Gwal
Robert Hanna
Jeffrey Helzer
Scott Hietpas
Werner Hoelzl
Robert Hoerauf
Richard Jackson
Song Jin
Andrew Jones
Laszlo Kadar
Innocent Kamwa
John Kay
Sheldon Kennedy
Isidoro Kerszenbaum
Yuri Khersonsky
Jim Kulchisky
Raluca Lascu
Michael Lauxman
Timothy Lensmire
Duane Leschert
Albert Livshitz
Omar Mazzoni
William McBride
John McQuilkin
John Merando
James Michalec
Daleep Mohla
Charles Morgan
Jerry Murphy
Edrin Murzaku
Dennis Neitzel
Rhonda Netzel
Arthur Neubauer
Michael Newman
Nick S. A. Nikjoo
Joe Nims
Gearold O. H. Eidhin
T. W. Olsen
Carl Orde
Lorraine Padden
Mirko Palazzo
Antony Parsons
Bansi Patel
Dhiru Patel
Subhash Patel
Shawn Patterson
Howard Penrose
Branimir Petosic
Louie Powell
Iulian Profir
John Ready
Samala Santosh Reddy
Charles Rogers
Thomas Rozek
Steven Sano
Todd Sauve
Bartien Sayogo
Ted Schoenberg
Nikunj Shah
Michael Simon
Jerry Smith
Gary Smullin
Wayne Stec
K. Stump
Paul Sullivan
David Tepen
James Thompson
Michael Thompson
Wayne Timm
Remi Tremblay
Richard Tressler
Demetrios Tziouvaras
Joe Uchiyama
Nijam Uddin
Marcelo Valdes
James Van De Ligt
Gerald Vaughn
John Vergis
James Volk
Daniel Ward
Kenneth White
Kenneth White
James Wolfe
Dean Yager
Larry Yonce
Jian Yu
David Zech

Introduction

This introduction is not part of IEEE Std 3002.7-2018, IEEE Recommended Practice for Conducting Motor-Starting Studies and Analysis of Industrial and Commercial Power Systems.

IEEE 3000 Standards Collection™

This recommended practice was developed by the Technical Books Coordinating Committee of the Industrial and Commercial Power Systems Department of the Industry Applications Society, as part of a project to repackage the popular IEEE Color Books®. The goal of this project is to speed up the revision process, eliminate duplicate material, and facilitate use of modern publishing and distribution technologies.

When this project is completed, the technical material included in the 13 IEEE Color Books will be included in a series of new standards—the most significant of which will be a new standard, IEEE Std 3000™, IEEE Recommended Practice for the Engineering of Industrial and Commercial Power Systems. The new standard will cover the fundamentals of planning, design, analysis, construction, installation, startup, operation, and maintenance of electrical systems in industrial and commercial facilities. Approximately 60 additional dot standards, organized into the following categories, will provide in-depth treatment of many of the topics introduced by IEEE Std 3000:

— Power Systems Design (3001 series)

— Power Systems Analysis (3002 series)

— Power Systems Grounding (3003 series)

— Protection and Coordination (3004 series)

— Emergency, Standby Power, and Energy Management Systems (3005 series)

— Power Systems Reliability (3006 series)

— Power Systems Maintenance, Operations, and Safety (3007 series)

In many cases, the material in a dot standard comes from a particular chapter of a particular IEEE Color Book. In other cases, material from several IEEE Color Books has been combined into a new dot standard.

IEEE Std 3002.7

This recommended practice, from the commonly known *IEEE Brown Book*™, is intended as a practical, general treatise on motor-starting analysis and as an engineer's reference source on the techniques that are most commonly applied to the computer-aided motor-starting analysis of electric power systems in industrial plants and commercial buildings. IEEE Std 3002.7™ is a useful supplement to several other power system analysis texts that appear in Clause 2 (Normative reference) and Annex A (Bibliography). IEEE Std 3002.7 is both complementary and supplementary to the rest of the Color Book series.

This recommended practice describes how to conduct motor-starting studies and analysis of industrial and commercial power systems. It is likely to be of greatest value to the power-oriented engineer with limited experience in this area. It can also be an aid to all engineers responsible for the electrical design of industrial and commercial power systems.

All sections have been revised and updated—in some cases quite substantially—to reflect current technology and methodology for the computer simulation of power systems.

To many members of the working group who wrote and developed the original recommended practice, the *IEEE Brown Book* was a true labor of love. The dedication and support of each individual member was clearly evident in every chapter of the *Brown Book* and is also reflected in IEEE Std 3002.7. These individuals deserve our many thanks for their excellent contributions.

Contents

IEEE Recommended Practice for Conducting Motor-Starting Studies and Analysis of Industrial and Commercial Power Systems

1. Overview

1.1 Scope

This recommended practice describes how to conduct motor-starting studies and analysis of industrial and commercial power systems. It is likely to be of greatest value to the power-oriented engineer with limited experience in this area. It can also be an aid to all engineers responsible for the electrical design of industrial and commercial power systems.

2. Normative reference

The following referenced document is indispensable for the application of this document (i.e., it must be understood and used, so it is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEEE Std 399™, IEEE Recommended Practice for Industrial and Commercial Power Systems Analysis (*IEEE Brown Book*™).[1, 2]

---

[1] The IEEE standards or products referred to in Clause 2 are trademarks owned by The Institute of Electrical and Electronics Engineers, Incorporated.

[2] IEEE publications are available from The Institute of Electrical and Electronics Engineers (http://standards.ieee.org/).

3. Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.[3]

accelerating torque: The amount of torque available to accelerate the motor and load at any instant in time. Accelerating torque is the difference between the torque available from the motor at the motor output shaft, and the required load torque of the load system as seen at the connection to the motor shaft. Accelerating torque varies with the instantaneous speed of the system.

armature resistance: R_a, the direct-current armature resistance. This is determined from a dc resistance measurement.

armature: The main current carrying winding of a machine, usually the stator.

breakdown torque or **maximum torque:** The maximum shaft output torque that an induction motor (or a synchronous motor operating as an induction motor) develops when the primary winding is connected for running operation, at normal operating temperature, with rated voltage applied at rated frequency. This is also the peak of the torque–slip curve at rated voltage.

NOTE—A motor with a continually-increasing torque as the speed decreases to standstill is not considered to have a breakdown torque.[4]

direct axis: The machine axis that represents a plane of symmetry in line with the no-load field winding.

direct-axis saturated subtransient reactance: X''_{dv} (rated voltage) is the apparent reactance of the stator winding at the instant short-circuit occurs with the machine at rated voltage, no load. This reactance determines the current flow during the first few cycles after short-circuit.

direct-axis unsaturated subtransient reactance: X''_{di} (rated current) is the reactance that is determined from the ratio of an initial reduced-voltage open-circuit condition and the currents from a three-phase fault at the machine terminals at rated frequency. The initial open-circuit voltage is adjusted so that rated current is obtained for the level of the short-circuit current. The impedance is determined from the currents during the first few cycles.

direct-axis saturated synchronous reactance: X_d (machine base) is the ratio of reactive armature voltage to direct-axis armature current at rated frequency and voltage.

direct-axis saturated transient reactance: X'_{dv} (rated voltage) is the apparent reactance of the stator winding several cycles after initiation of the fault with the machine at rated voltage, no load. The time period for which the reactance may be considered X'_{dv} can be up to a half second or longer, depending upon the design of the machine and is determined by the machine direct-axis transient time constant.

direct-axis unsaturated transient reactance: X'_{di} (rated current) is the reactance that is determined from the ratio of an initial reduced-voltage open-circuit condition and the currents from a three-phase fault at the machine terminals at rated frequency. The initial open-circuit voltage is adjusted so that rated current is obtained for the level of the short-circuit current. The initial high decrement currents during the first few cycles are neglected.

[3] *IEEE Standards Dictionary Online* subscription is available at: http://dictionary.ieee.org.
[4] Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

ferroresonance: A type of resonance in electric circuits which occurs when a circuit containing a non-linear inductance is fed from a source that has series capacitance, and the circuit is subjected to a disturbance such as the opening of a switch.

field: The exciting or magnetizing winding of a machine.

frequency: The operating frequency of a circuit.

full-load torque: The shaft torque necessary to produce rated output power at full-load speed.

inrush current: The rapid change of current with respect to time upon motor energization. Inrush current depends on the voltage impressed across the motor terminals and the motor inductance by the relationship $V = L \times \frac{di}{dt}$.$\boldsymbol{V = L \times \frac{di}{dt}}$

load torque: The shaft torque necessary to produce the required power output at required speed.

locked-rotor current: The steady-state current taken from the line with the rotor locked and with rated voltage and rated frequency applied to the motor.

motor slip: The quotient of the difference between the synchronous speed and the actual speed of a rotor, to the synchronous speed, expressed as a ratio, or as a percentage.

motor-starting torque, breakaway, or locked-rotor torque: The torque output capability of the motor at zero speed and rated voltage and frequency. It may also be defined as the minimum torque of a motor developed for all angular positions of the rotor when at rest, and with rated voltage and frequency applied.

positive sequence: A set of symmetrical components that have the angular phase lag from the first member of the set to the second and every other member of the set equal to the characteristic angular phase difference and rotating in the same phase sequence of the original vectors. For a three-phase system, the angular different is 120°.

positive sequence machine resistance: R_1 is that value of rated frequency armature resistance that, when multiplied by the square of the rated positive-sequence armature current and by the number of phases, is equal to the sum of the copper loss in the armature and the load loss resulting from the flow of that current.

pull-in torque: The maximum load torque under which the motor will pull its connected inertia (WR^2) into synchronism at rated voltage and frequency when excitation is applied. Note that inertia of the rotating system consists of motor, load, and coupling inertia.

pull-out torque: The maximum steady-state torque developed by the motor for 1 minute before it pulls out of step due to overload.

pull-up torque: The minimum torque developed by the motor during the period of acceleration from rest to the speed at which breakdown torque occurs with rated voltage applied at rated frequency.

quadrature axis: The machine axis that represents a plane of symmetry in the field that produces no magnetization. This axis is 90° ahead of the direct axis.

quadrature-axis saturated subtransient reactance: X''_{qv} (rated voltage) is the apparent reactance of the stator winding at the instant short-circuit occurs with the machine at rated voltage, no load, in quadrature axis. This reactance determines the current flow during the first few cycles after short-circuit..

quadrature-axis unsaturated subtransient reactance: X''_{qi} (rated current) is the reactance in quadrature axis that is determined from the ratio of an initial reduced-voltage open-circuit condition and the currents from a three-phase fault at the machine terminals at rated frequency. The initial open-circuit voltage is adjusted so that rated current is obtained for the level of the short-circuit current. The impedance is determined from the currents during the first few cycles.

quadrature-axis synchronous reactance: X_q is the ratio of reactive armature voltage to quadrature-axis armature current at rated frequency and voltage.

quadrature-axis saturated transient reactance: X'_{qv} (rated voltage) is the apparent reactance of the stator winding several cycles after initiation of the fault with the machine at rated voltage, no load, in quadrature axis.

quadrature-axis unsaturated transient reactance: X'_{qi} (rated current) is the reactance that is determined from the ratio of an initial reduced-voltage open-circuit condition and the currents from a three-phase fault at the machine terminals at rated frequency in quadrature axis. The initial open-circuit voltage is adjusted so that rated current is obtained for the level of the short-circuit current. The initial high decrement currents during the first few cycles are neglected.

rating: The designated operating characteristics of a device, usually at some prescribed load.

rms: The square root of the average value of the square of the voltage or current taken throughout one period. In this text, rms will be considered total rms unless otherwise noted.

service factor: It is the percentage of overloading the motor can handle for short periods when operating normally within the correct voltage tolerances.

stator: The stationary member of a machine.

symmetrical components: A symmetrical set of three vectors used to mathematically represent an unsymmetrical set of three-phase voltages or currents. In a three-phase system, one set of three equal magnitude vectors displaced from each other by 120° in the same sequence as the original set of unsymmetrical vectors. This set of vectors is called the positive sequence component. A second set of three equal magnitude vectors displaced from each other by 120° in the reverse sequence as the original set of unsymmetrical vectors. This set of vectors is called the negative sequence component. A third set of three equal magnitude vectors displaced from each other by 0°. This set of vectors is called the *zero sequence component.*

symmetrical current: That portion of the total current that, when viewed as a waveform, has equal positive and negative values over time, such as is exhibited by a pure single-frequency sinusoidal waveform.

synchronous torque: Steady-state (load dependent) torque developed during operation.

***X/R* ratio**: The ratio of rated frequency reactance and effective resistance to be used for short-circuit calculations.

4. Introduction

4.1 Overview

Motors on modern industrial systems are becoming increasingly larger. Some are considered large even in comparison to the total capacity of large industrial power systems. Starting large motors, especially across-the-line, can cause severe disturbances to the motor and any locally-connected load, and also to buses electrically remote from the point of motor starting. Improper motor start-up can cause damage to the motor, power quality problems (such as brownouts), or even service disruptions.

Ideally, a motor-starting study should be conducted before a large motor is purchased, such that the motor can be installed with confidence that the motor's life and applications performance will be satisfactory and the remainder of the power distribution system will not be adversely affected. It may also be performed anytime a change in the power supply is implemented. A starting voltage requirement and preferred locked-rotor current should be stated as part of the motor specification.

This recommended practice, from the commonly-known IEEE Std 399™ (*IEEE Brown Book*™), discusses benefits obtained from motor-starting studies and examines various types of computer-aided studies normally involved in motor-starting studies. Data or information required for these studies as well as the expected results of a motor-starting study effort are also presented and reviewed.

4.2 Motor fundamentals

An electric motor is an electromechanical device that converts electrical energy into mechanical energy. Most electric motors operate through the interaction of magnetic fields and current-carrying conductors to generate force. The reverse process, producing electrical energy from mechanical energy, is done by generators such as an alternator or a dynamo; some electric motors can also be used as generators; for example, a traction motor on a vehicle may perform both tasks. Electric motors and generators are commonly referred to as *electric machines*.

4.3 Motor horsepower versus torque

When ordering a motor, one refers to its basic ability for converting electrical to mechanical energy by specifying its horsepower (see Figure 1.) Yet, it will be found that most of the manufacturer's data deal with torque. A little contemplation reveals the reason for this. It turns out that torque, the turning effort, is more fundamental than horsepower, which is the rate of supplying energy. Horsepower is the product of torque multiplied by speed, so that a given horsepower can correspond to a high torque and low speed, or to the converse combination. In practical applications, one is usually specifically interested in knowing the torque and the speed separately as they apply to the load on the motor. One should note that speed is very easily measured. Because of these considerations, the graphs of motor performance will either depict torque as the function of some other parameter, such as armature current, or alternatively some parameter, such as speed, as a function of torque. More quantitatively, torque itself is the product of the force developed at the rim of a disc, cylinder, or wheel multiplied by the distance to the center. Thus, pound-feet is a common unit for this measurement. The relationship between motor-rated power and its rated torque is given below:

$$T = \frac{33\,000 \times HP}{2\pi \times RPM} \text{ in lb-ft} \quad (1)$$

$$T = \frac{59\,994 \times kW}{2\pi \times RPM} \text{ in N-m} \qquad (2)$$

where

T is motor-rated torque

HP is motor-rated output power in horsepower

kW is motor-rated power

RPM is motor-rated speed

A practical manifestation of what has been said is that the horsepower output of a motor at standstill is zero. Even giant motors develop zero horsepower at the instant an attempt is made to start them. On the other hand, torque, and specifically starting torque, tells us what we want to know about starting capability. Indeed, this performance characteristic is one of the primary considerations in motor selection and application.

In a general way, horsepower, because it is specified at a rated speed, motor current, and motor voltage (and frequency), can provide guidance in selection of the size of the motor. However, in order to know whether it will serve a particular application, we must ascertain that the right combination of speed and torque can be delivered.

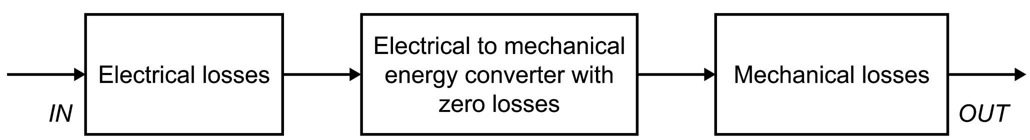


Figure 1—Motor electric power to mechanical power conversion

4.4 Starting torque and acceleration

The motor must provide sufficient torque to accelerate within its thermal rating. The torque available to accelerate at any point on the speed–torque curve is the difference between the motor torque and the load torque (see Figure 2). Because the motor torque varies approximately with the voltage squared, it must be adjusted for voltage drop during starting. If the acceleration torque produced by the motor is insufficient to bring the machine to its operating speed within the permissible time, the motor may suffer from rotor or stator damage.

Note that, typically, torque and speed characteristics can be obtained from motor manufacturers at 100% and 80% starting voltage.

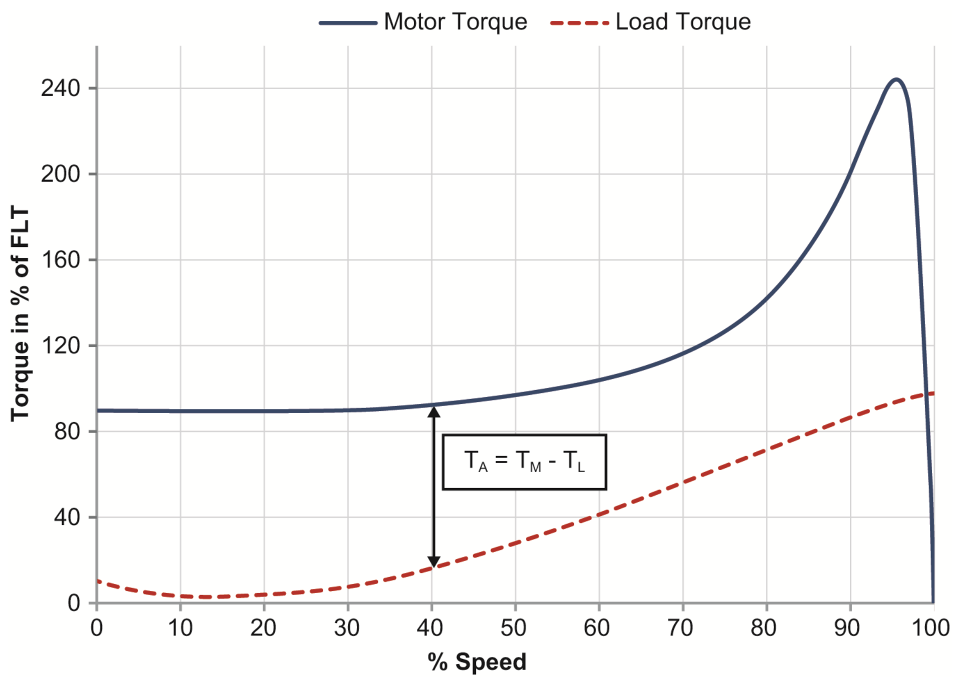


Figure 2—Motor torque/speed curve

Where

T_L	is load torque (N-m or lb-ft)
T_M	is motor torque (N-m or lb-ft)
T_A	is $(T_M – T_L)$ accelerating torque (N-m or lb-ft)
N	is operating speed in RPM
n_S	is synchronous speed in RPM
1 lb-ft	is 1.355 818 N-m

4.5 AC and DC machines

Electric motors represent an important fraction of residential, commercial, and industrial loads; approximately 60% of the electrical energy in the United States is utilized by motors of some kind. Motor loads comprise fans, pumps of all kinds, including refrigerators and air conditioners, power tools from hand drills to lawn mowers, and even electric streetcars—basically, anything electric that moves.

Aside from differences in size and power, there are three distinct types of motors; namely induction, synchronous, and direct current (dc). Besides motor type, another important distinction is between single-phase and three-phase motors. A three-phase motor benefits from the constant torque afforded by three separate windings, staggered in space and time, that in combination produce a rotating magnetic field of

constant strength (this applies only to alternating-current [ac], not dc machines). Three-phase motors, therefore operate more smoothly and much more efficiently than single-phase motors.

Three-phase motors are commonly used for large industrial and commercial applications where high performance, including high horsepower output and high efficiency, is essential, and where three-phase utility service is standard. Smaller commercial and almost all residential customers receive only single-phase service because of the significant cost difference in distribution. It is technically possible, however, to operate a three-phase motor on single-phase service by inserting an electronic phase-shifting device that effectively splits the voltage and current along several circuits and changes their relative timing to produce three staggered sine waves. Motor-generator apparatus can also be used to operate three-phase motors on single-phase services.

4.6 AC machines

4.6.1 Overview

Two classes of ac motors are recognized—induction (asynchronous) motor and synchronous motor. An asynchronous or induction motor requires slip—relative movement between the magnetic field generated by the stator and a winding set (the rotor) to induce current in the rotor by mutual inductance. The most ubiquitous example of asynchronous motors is the common ac induction motor which must slip to generate torque.

In the synchronous types, induction (or slip) is not a requisite for magnetic field or current production. In synchronous machines, rotor-winding currents are supplied directly from the stationary frame through a rotating contact or induced via a brushless excitation mechanism.

4.6.2 Induction motor

An induction machine is an asynchronous machine that comprises a magnetic circuit which interlinks with two electric circuits, rotating with respect to each other and in which power is transferred from one circuit to the other by electromagnetic induction. An induction motor is an induction machine which transforms electric power into mechanical power, and in which one member (usually the stator) is connected to the power source, and a secondary winding on the other member (usually the rotor) carries induced current.

The ac induction motor is the most common type of industrial motor. The common ac polyphase squirrel-cage induction motor does not require commutator, brushes, or slip rings. It has the fewest windings, least insulation, and lowest cost per horsepower when compared to other motors, such as single-phase or synchronous motors. Therefore, it has become the most widely used industrial motor (see Donner, Subler, and Evon [B10][5]).

The two main electrical components of an ac induction motor are the stator and the rotor. The stator is the stationary primary side, and the rotor is the rotating secondary part of the motor. The power is transmitted to the rotor inductively from the stator through transformer action.

The polyphase ac induction motor is connected to a three-phase power supply. The currents in a three-phase power supply are displaced by 120 electrical degrees. The current in phase A reaches its positive maximum 120° ahead of phase B, and the current in phase B will be 120° ahead of phase C. A plot of three-phase current of an induction motor can be seen in Figure 3 (ABC rotation).

[5] The numbers in brackets correspond to those of the bibliography in Annex A.

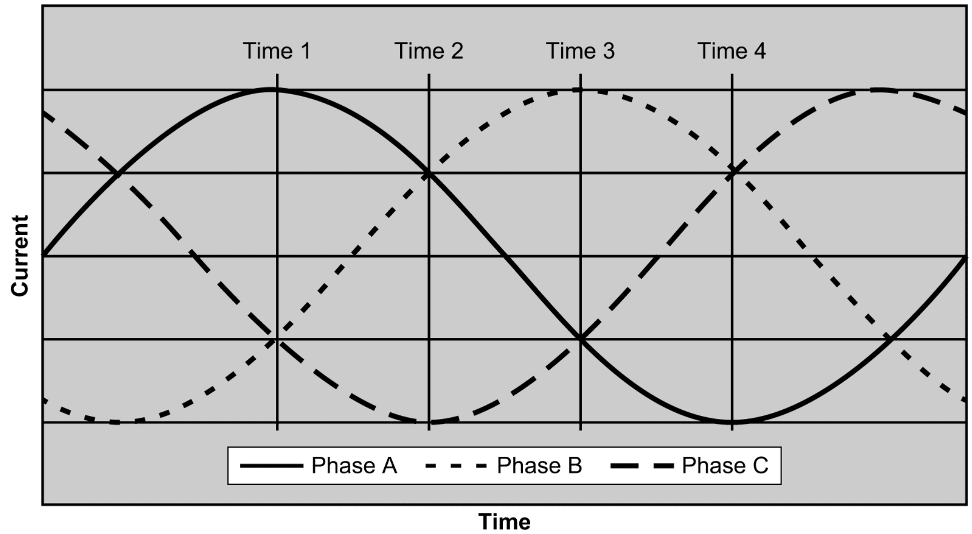


Figure 3—Plot of three-phase current of an induction motor

The stator for a two-pole three-phase ac induction motor is schematically represented in Figure 4. The pole pairs for each phase are represented in the schematic where the direction and magnitude of the fluxes in all three phases (Φ_A, Φ_B, and Φ_C) are shown as vectors. The vectors represent four moments in time as indicated in Figure 3. The resultant flux vector is represented as Φ_R. The rotation of the resultant flux vector is clockwise.

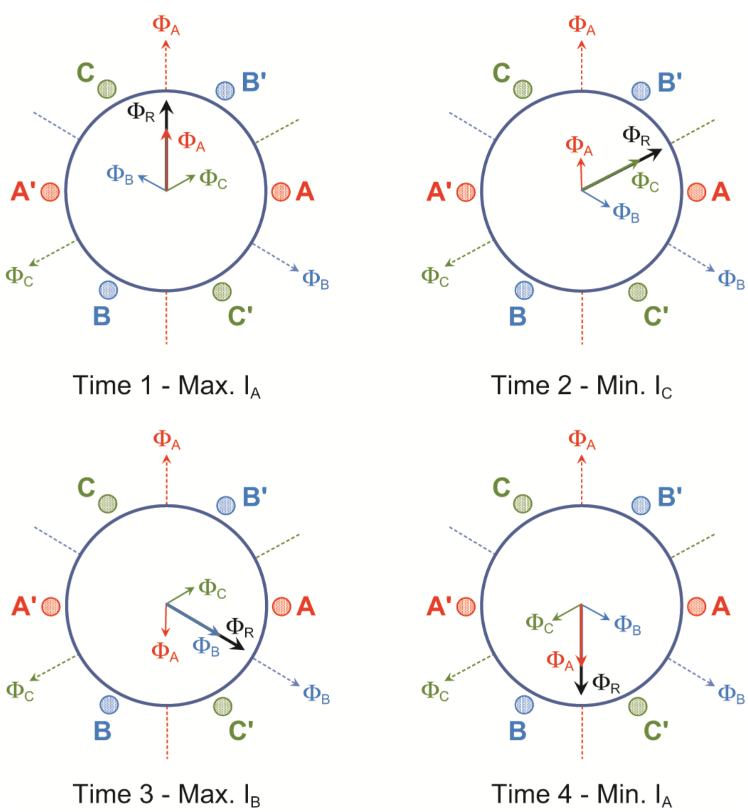


Figure 4—Flux vectors versus time

Time 1: The current in phase A is at its positive maximum as seen in Figure 3. The currents for phases B and C are at half of their negative maximums. The flux vectors for each phase can be seen in Figure 4, time 1. Using vector addition, the resultant flux vector (Φ_R) is equal to 3/2 of the maximum flux per phase and located at the 12 o'clock or 0° position.

Time 2: Phase C current is now at its negative maximum with phases A and B at half of their positive maximums. The resultant flux vector is then equal to 3/2 of the maximum and located at 2 o'clock or 60° position. The resultant vector has rotated clockwise 60° from the position in time 1. Therefore, for a 60° change in time the resultant vector has rotated 60°.

Time 3: Phase B current is now at its positive maximum with phases A and C at half of their negative maximums. The resultant flux vector is then equal to 3/2 of the maximum and located at the 4 o'clock or 120° position.

Time 4: Phase A current is now at its negative maximum with phases B and C being at half of their positive maximums. The resultant flux vector is again 3/2 of the maximum and located at the 6 o'clock or 180° position.

The resultant flux vector rotated 180° clockwise from time 1 to time 4 or half of a cycle. This half of a cycle caused the resultant flux vector, which represents the rotor, to rotate one pole. The rotor would then rotate two poles for the entire cycle or 360°. Therefore, for a two-pole motor, one cycle will produce one rotation. If the motor was a four-pole motor, the resultant flux vector would also rotate two poles for one cycle. However, a rotation of two poles in a four-pole motor is equal to a 180°. The four-pole motor would require 2 cycles for one revolution.

Therefore, the relationship between motor speed and number of poles can be seen as:

$$n_s = \frac{120 \times f}{P} \qquad (3)$$

where

n_s is synchronous speed in RPM

f is frequency

P is the number of poles

The synchronous speed (revolutions per minute, RPM), is inversely proportional to the number of poles. Also, motor slip can be expressed as:

$$\%\ \text{slip} = \frac{n_s - n}{n_s} \times 100 \qquad (4)$$

where

n_s = synchronous speed in RPM

n = motor speed in RPM

Note that there are two common variations of induction motor: squirrel-cage and wound rotor:

— Squirrel-cage induction motor: The rotor circuit consists of a number of conducting bars shorted by rings at both ends.

— Wound rotor induction motor: The rotor circuit consists of an insulated winding whose terminals are either short-circuited or closed through external circuits. The rotor has a winding the same as stator, and the end of each phase is connected to a slip ring. Also, three brushes contact the three slip-rings to three connected resistances for reduction of starting current and speed control.

4.6.3 Synchronous motor

A synchronous machine is an alternating-current machine in which the speed of operation is exactly proportional to the frequency of the system to which it is connected. The stator winding is similar to the induction-motor winding. The rotor consists of salient poles, field pole winding, and amortisseur or damper or cage windings. Infrequently-used high speed (typically 3600 RPM) synchronous motors may use cylindrical rotors. The amortisseur winding consists of cage bars embedded in the pole faces and short-circuited at each end by the end rings. Field poles are magnetized by dc from the rotating exciter mounted on the same shaft. The rotor winding consists of an insulated-field winding, wound to produce the magnetic poles equal in number to the poles for which the stator is wound.

The motor starts as an induction motor, and the shape of the speed–torque curve depends on the resistance and reactance of the amortisseur winding. DC excitation is applied to the field winding at a speed known as pull-in speed when the motor torque equals the load torque. The dc field excitation keeps the rotor speed in synchronism with that of the rotating field produced by the stator. The motor will pull the connected load into synchronism upon the application of the dc field. During starting, the field winding is short-circuited through a field-discharge resistor to limit the induced voltage.

Synchronous motors are classified as high-speed machines when RPM is > 500, and low-speed machines when RPM is < 500. In certain applications, the synchronous motors are preferred over squirrel-cage induction motors for the following reasons:

— Operate at a leading power factor and thereby improve the overall power factor of the plant power system

— Less costly in certain horsepower and speed ranges, especially at speeds less than 600 RPM. Synchronous motors are cost effective when HP/RPM is > 5 or kW/RPM is > 6.7

— Constructed with wider air gaps than induction motors, which make them more robust mechanically and facilitates ease of maintenance

— Higher efficiency, on the order of 1.5% to 2% higher.

The synchronous motor is further classified as the direct-current excited synchronous motor (usually called the synchronous motor), the permanent-magnet synchronous motor, and the reluctance synchronous motor. The different types of torques developed by a synchronous motor are as follows:

— Starting or breakaway torque

— Pull-up torque

— Synchronous torque

— Pull-out torque

— Maximum torque

— Pull-in torque

During starting and acceleration as an induction motor, the synchronous motor develops a pulsating or oscillating torque superimposed on the average torque. The frequency of this torque is equal to twice the slip frequency. For a 60 Hz system, the oscillating torque will go through all frequencies from 120 Hz to 0 Hz. The inertia system of a rotating motor which has one or more natural torsional frequencies at or

below twice the line frequency will be excited. When this condition occurs, there is a possibility of torsional resonance occurring with torque amplifications. A steady-state and dynamic analysis is required for the complete drive train (including motor, coupling, gear, and driven equipment) to determine the magnitude of the torque amplification. Either the mechanical or electrical equipment vendor, or both, shall be asked to carry out this analysis. If excessive torque amplification is identified, then necessary steps must be taken to reduce its magnitude to an acceptable level. This analysis however is outside the scope of IEEE Std 3002.7™.

4.7 DC machines

4.7.1 Overview

A direct-current machine is a machine consisting of a rotating armature winding connected to a commutator and stationary magnetic poles that are excited from a direct-current source or permanent magnets. Direct-current motors are of four general types: shunt-wound, permanent-magnet, series-wound, and compound-wound (Beaty and Kirtley [B2]).

4.7.2 DC shunt motor

A shunt-wound motor may be a straight shunt-wound or a stabilized shunt-wound motor. In a straight shunt-wound motor, the field winding is connected in parallel with the armature circuit or to a source of separate excitation voltage. The shunt field is the only winding supplying field excitation. The stabilized shunt motor has two field windings: the shunt and the light series. The shunt-field winding is connected either in parallel with the armature circuit or to a separate source of excitation voltage. The light series winding is connected in series with the armature winding, and is added to prevent a rise of speed or to obtain a slight reduction of speed with increase in load.

A salient feature of the dc shunt motor is its reversibility. The direction of rotation may be reversed by changing the direction of current flow in either the shunt field winding or in the armature, but not in both. Moreover, such rotational reversal can be accomplished by “plugging,” that is by reversing one of the currents while the motor is in normal operation. In this way, it becomes unnecessary to wait while the motor coasts down to a standstill. The general characteristics of a dc shunt motor is shown in Figure 5.

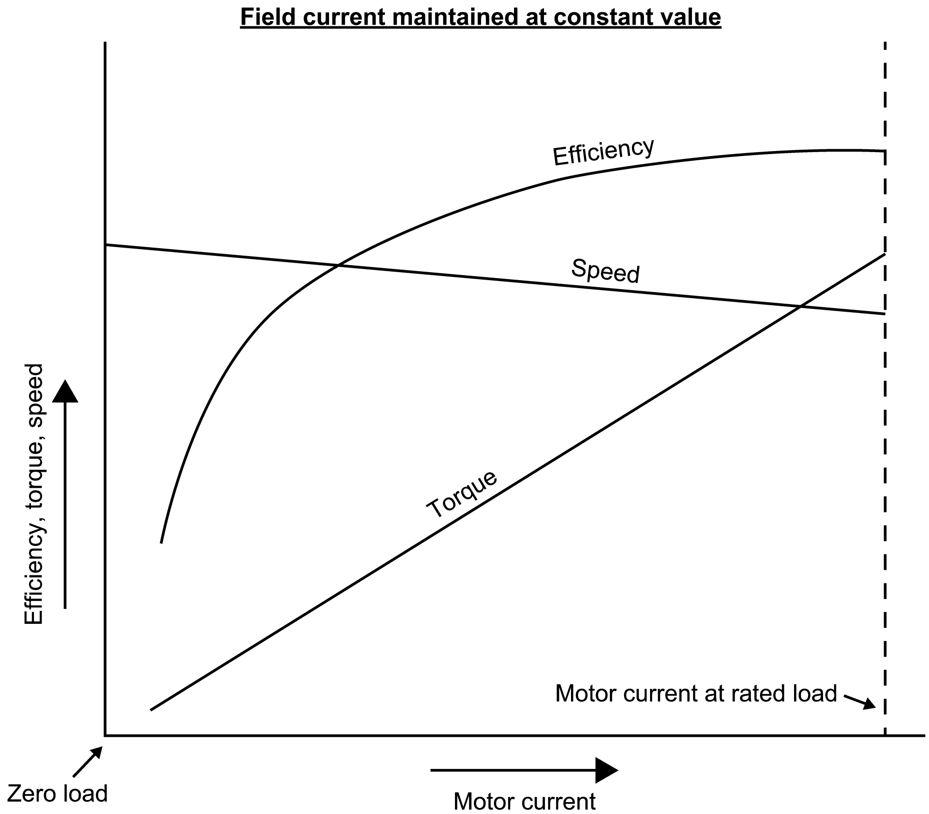


Figure 5—General characteristics of a dc shunt motor

4.7.3 DC permanent magnet (PM) motor

More recently, PM motors have benefited greatly from advanced-technology ceramic and alloy magnetic materials. On a horsepower-output basis, the PM motor can now be appreciably smaller and lighter than an equivalently-rated shunt motor. The starting torque can be several times greater than a shunt motor with otherwise-similar ratings. Their speed–torque relationship is very linear over a wide range, and therefore is easy to predict.

These characteristics of the dc PM motor are depicted graphically in Figure 6(a). It is interesting to observe from Figure 6(b) that, for a wide range of applied armature voltages, the speed–torque characteristics remain linear all the way down to a standstill as more torque is delivered.

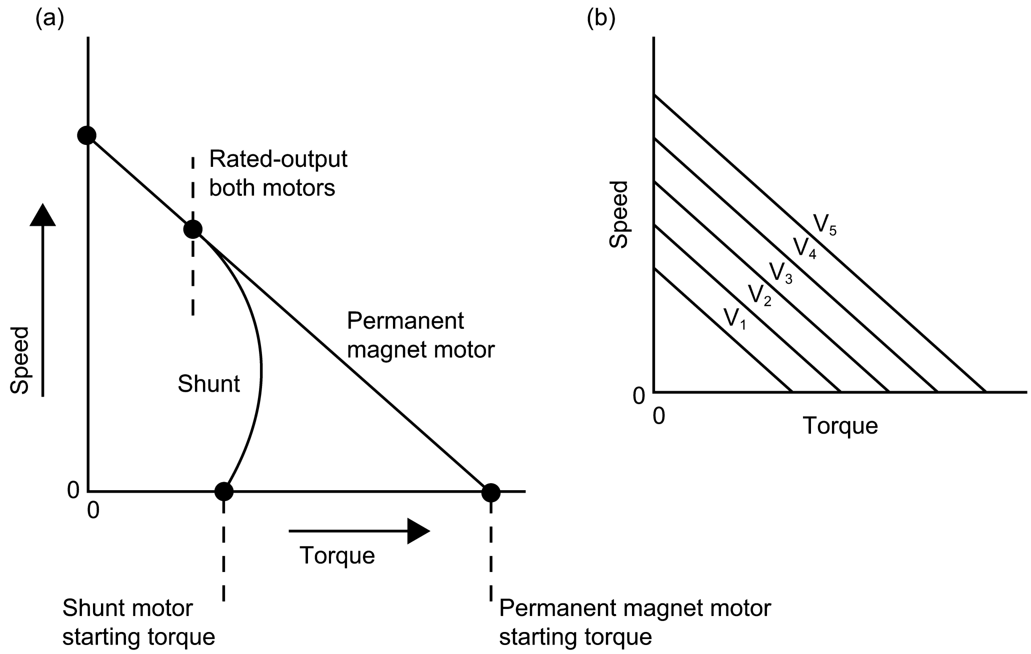


Figure 6—Unique torque-speed characteristics of a PM motor

Permanent magnet dc motors tend to exhibit better (lower) speed regulation than do shunt motors. In this regard, they compare favorably with ac induction motors. Their operating efficiency, too, tends to exceed that of shunt motors. Not only is the PM motor amenable to armature voltage control of its speed, but usually its good performance is also continuous when its direction of rotation is reversed by reversal of the polarity of the applied armature voltage. It has also been observed that when the PM motor is controlled by an audio-frequency pulse-width-modulation wave, operation is quieter than it would be in a similarly-controlled shunt motor. There, the need to use higher operating frequencies for the sake of noise reduction can be electrically undesirable.

An important practical benefit of making use of a permanent magnet field structure is immunity to run away. As is well known, if for any reason the dc shunt motor is deprived of field current, the motor goes into a runaway mode. Even if it is fully loaded, the racing, together with abnormally-high armature current, can pose a hazardous situation.

Note that specialized ac permanent magnet motors are not part of the scope of this document. Refer to the motor manufacturer for additional details. In general, PM ac motors are inherently more efficient due to the elimination of rotor conductor losses, lower resistance winding, and a “flatter” efficiency curve. Due to their synchronous operation, these motors offer more precise speed control with higher power density due to the higher magnetic flux as compared with induction machines and generally operate cooler, resulting in longer bearing and insulation life.

4.7.4 DC series motor

The dc series motor is one of the traditional “workhorses” of electromechanical energy conversion. Its popularity with railway, automobile, and other traction applications largely stems from the very high torque developed by this motor at standstill and at low speeds. The torque is high because armature current flows through both; the armature and the series field giving rise to an exceptionally-strong magnetic field between the armature conductors and the pole faces. The motor obligingly supplies greater torque in

response to shaft loading until a limit is imposed because of magnetic saturation. The older control method via a series-connected resistance wasted energy and sufficed for trams, but is unacceptable for electric automobiles. On the other hand, control by duty-cycle modulation of pulsed waveforms is extremely efficient and allows smooth variation of speed and torque.

If deprived of its mechanical load, a dc series motor will accelerate to very high speeds. See Figure 7. Indeed, such racing can culminate in centrifugal explosion of the armature, and it would be hazardous for an operator to be anywhere close to such a self-destroying machine. One might say that the unloaded motor develops too much torque for its own good due to the multiplying effect of the internal field being the product of both the armature and series field current. This abundant torque manifests itself as speed acceleration. At some extremely high speed, the unloaded motor would develop enough counter electromotive force, so that armature and field current would again be relatively low; the acceleration would then come to a halt. Unfortunately, before such a new equilibrium can be attained, the motor could be expected to destroy itself.

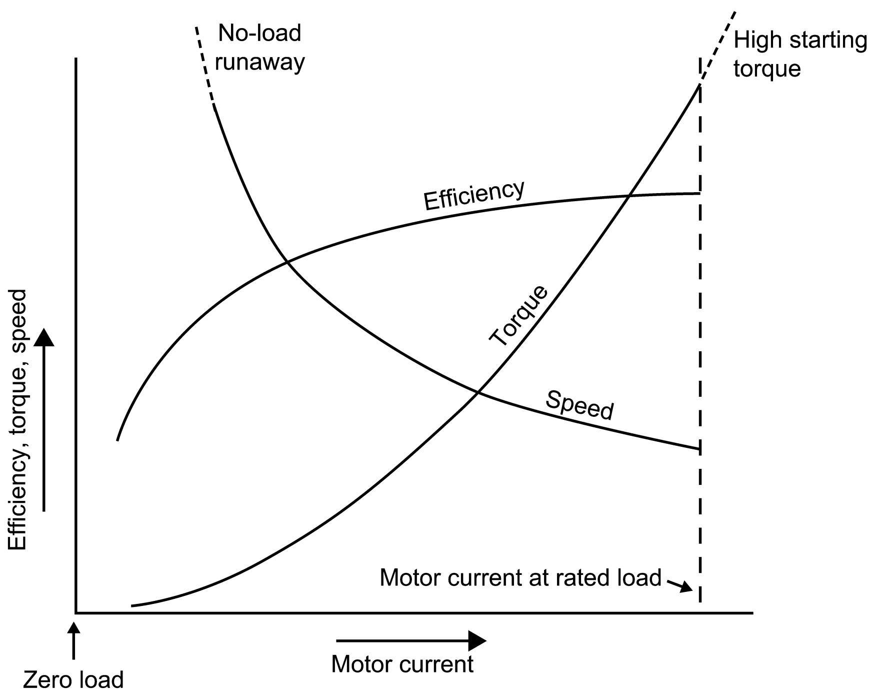


Figure 7—General characteristics of a dc series motor

4.7.5 DC compound motor

The dc compound motor has both series-connected and shunt-connected field windings. By varying the polarization and the current in these field windings, the motor can be made to behave as a series motor, a shunt motor, or a motor exhibiting various blends of series and shunt motor characteristics.

The current in the series-field winding can be diverted by means of a resistance connected across its terminals. Control of the current in the shunt-field winding is achieved by a series-connected rheostat, just as in a “plain vanilla” shunt-motor.

5. Motor standards

5.1 Overview

The motor standards can be grouped into two major categories: NEMA and IEC (and its derivatives). In North America, the National Electric Manufacturers Association (NEMA) sets motor standards, including what should go on the nameplate (NEMA MG1). In other parts of the world, the International Electrotechnical Commission (IEC) sets the standards, or at least many countries base their standards very closely on the IEC standards. For example, Germany's VDE 0530 standard and Great Britain's BS 2613 standard are close to IEC with minor exceptions. Note that the major IEC standard for motor is IEC 60034 series.

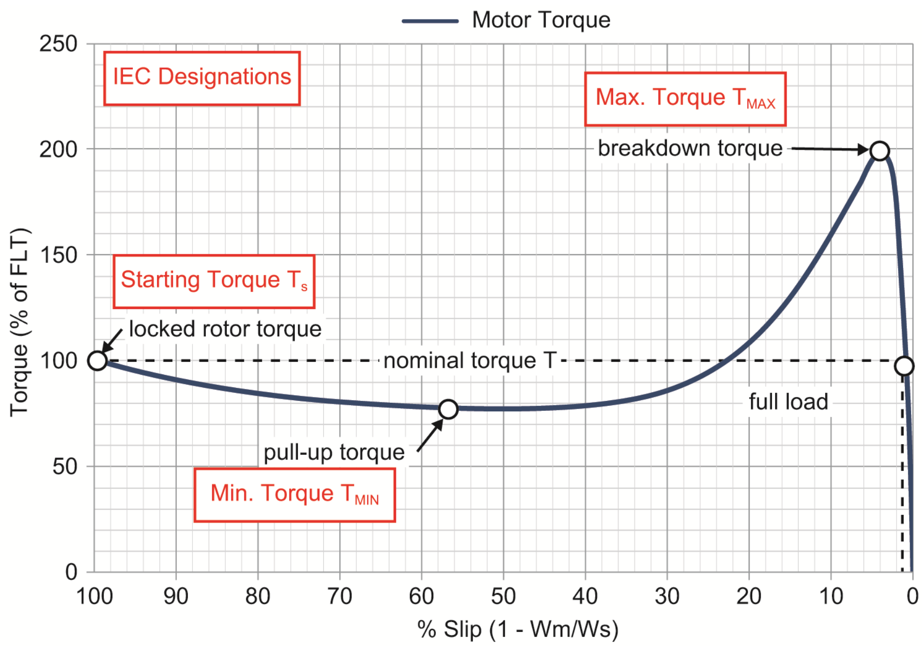
NEMA MG1 [B37] specifies that every motor nameplate must show these specific items:

- Manufacturer's type
- Rated volts and full-load amps
- Rated frequency and number of phases
- Rated full-load speed
- Rated temperature rise or the insulation system class
- Time rating
- Rated horsepower
- Locked-rotor indicating code letter
- Service factor
- Efficiency
- Frame size

Additional information may also normally appear on the nameplates depending on the motor vendor.

5.2 Comparison between NEMA and IEC motor standards

The IEC is the international counterpart to the NEMA standards. These two standards use different terms, but they are essentially analogous in ratings and, for most common applications, are largely interchangeable. In brief, NEMA standards tend to be more conservative, while IEC standards tend to be more precise, specific, and more categorized. For a more detailed comparison of these two motor standards, refer to Mistry, Finley, and Gaerke [B32]. Motor torque characteristics are compared and shown in Figure 8. Refer to Annex B for main differences between the two standards regarding motor description and testing.



NEMA designations	locked-rotor torque	pull-up torque	breakdown torque	nominal torque
IEC designations	starting torque	minimum torque	maximum torque	nominal torque

Figure 8—IEC and NEMA designations for the motor torque/speed curve

6. Analysis objectives

6.1 General purpose

A motor-starting study is performed to determine the voltages, currents, and starting times involved when starting large motors or a group of motors, either sequentially or simultaneously. Motor-starting studies are carried out to help ensure that:

- Motor(s) will start with appropriate/acceptable voltage drop
- Voltage drop at time of start will not disrupt other loads
- Motor feeder(s) are sized adequately
- Motor(s) will accelerate within acceptable start-up times
- An accurate evaluation of motor/load speed–torque characteristics and accelerating time is made
- An accurate evaluation of thermal damage characteristics of motors is made
- The motor will not experience nuisance tripping on the start
- In the event of direct on line (DOL) start is not possible, that the type and size of starter/drive required to start the motor is known
- Motor protective devices are sized/set properly

Following is a brief discussion of major problems associated with starting large motors, or groups of motors, and therefore, of significance in power system design and evaluation.

6.2 Criteria

Starting large motors can cause disturbances to the motor and other loads on other buses. In the worst cases, the starting motor may stall and be unable to start the driven load. In general, a motor-starting study should be made if the motor horsepower rating exceeds approximately 30% of the base kVA rating of the supplying transformer. Likewise, if a motor is to be started from an isolated generator, a motor starting study should be performed if the motor horsepower rating exceeds 10% to 15% (typical) of the generator kVA rating, depending on actual generator characteristics. The study should also recognize contingent condition(s), i.e., the loss of a source (if applicable).

Types of available motor-starting studies range from simple voltage drop calculation to a detailed waveform presentation of motor bus voltage; motor speed and motor torque; acceleration torque; load torque; power factor; rotor and stator currents; motor slip, real, reaction, and total power study that approaches a dynamic analysis in complexity. Each study has an appropriate use, and the selection of the correct study is as important a step in the solution process as the actual performance of the study itself. Examples presented here should serve as a guide for determining when to use each type of motor-starting study, what to expect in the way of results, and how these results can be beneficially applied. The examples should also prove useful in gathering the required information for the specific type of study chosen. Experienced consulting engineers and equipment manufacturers can give valuable advice, information, and direction regarding the application of motor-starting studies as well.

It may be necessary to make a study for smaller horsepower sizes depending on the daily fluctuation of nominal voltage, voltage level, size and length of the motor feeder cable, amount of load, regulation of the supply voltage, the impedance and tap ratio of the supply transformer(s), load torque versus motor torque, and the allowable starting time. Finally, some applications may involve starting large groups of smaller motors of sufficient collective size to impact system voltage regulation during the starting interval.

One of the most common side effects of starting large motors is a serious voltage dip on the buses throughout the facility. This voltage dip will cause other motors to slow down. In severe cases, other motors may reach the stall point causing a cascading drop in system voltage. Control relays may not hold, and auxiliary equipment may be affected. In addition to these secondary effects, the life of all motors on the system may be shortened. Motor-starting studies should determine the variation in voltage as a function of time during the period of acceleration of the motor. Motor-starting studies should be performed prior to the ordering of large motors, such that the motor can be installed with confidence that the motor's life and applications performance will be satisfactory, and the remainder of the power distribution system will not be adversely affected.

6.3 Voltage dips

Probably the most widely recognized and studied effect of motor starting is the voltage dip experienced throughout an industrial power system as a direct result of starting large motors. Available accelerating torque drops appreciably at the motor bus as voltage dips to a lower value, extending the starting interval and affecting, sometimes adversely, overall motor-starting performance. Acceptable voltage for motor starting depends on motor and load-torque characteristics. Requirements for minimum starting voltage can vary over a wide range, depending on the application (i.e., voltages can range from 80% or lower to 95% or higher). Refer also to Chapter 3 in IEEE Std 141™ for a discussion of voltage considerations.

A starting point for most motor-starting studies is an understanding of the minimum acceptable voltage that must be sustained on the system. During motor starting, the voltage level at the motor terminals should be maintained as specified by the motor manufacturer. This value is typically 80% of motor-rated voltage for a standard motor having a standard 150% starting torque at rated voltage (i.e., 100% voltage) and with a constant torque load applied. This value results from examination of speed–torque characteristics of a motor and the desire to successfully accelerate a fully-loaded motor at reduced voltage (i.e., torque varies

with approximately the square of the voltage, therefore, the new starting torque is about $T = 0.8^2 \times 150\% = 96\%$ of rated torque).

When other motors are affected, or when lower shaft loadings are involved, the minimum permissible voltage may be either higher or lower, respectively. The speed–torque characteristics of the starting motor along with any other affected motors and all related loads should be examined to specifically determine minimum acceptable voltage. Assuming reduced voltage permits adequate accelerating torque, it should also be verified that the longer starting interval required at reduced torque caused by a voltage dip does not result in the I^2t damage limit of the motor being exceeded.

Several other problems may arise on the electrical power system due to the voltage dips caused by motor starting. Motors that are running normally on the system, for example, will slow down in response to the voltage dip occurring when a large motor is started. The running machines must be able to reaccelerate once the machine being started reaches operating speed. When the voltage depression caused by the starting motor is severe, the loading on the running machines may exceed their breakdown torque (at the reduced voltage), and they may decelerate significantly, or even stall, before the starting interval is concluded. The decelerating machines all impose heavy current demands that only compound the original distress caused by the machine that was started. The result is a cascading voltage depression that can lead to the loss of all loads.

For example, if the motors on the system are standard NEMA B design, the speed–torque characteristics (e.g., 200% breakdown torque at full voltage) should prevent a stall, provided the motor terminal voltage does not drop below approximately 70% of motor nameplate voltage. This is a valid guideline to follow anytime the shaft load does not exceed 100% rated, since the developed starting torque is again proportional to the terminal voltage squared (V^2), and the available torque at 70% voltage would thus be slightly above 100%. Of course, if motors other than NEMA design B are used, a similar criterion can be established to evaluate reacceleration following a motor-starting voltage dip based on the exact speed–torque characteristics of each particular motor.

Other types of loads, such as electronic devices and sensitive control equipment, may be adversely affected during motor starting. There is a wide range of variation in the amount of voltage drop that can be tolerated by static drives and computers. Voltage fluctuations may also cause objectionable fluctuations in lighting. Tolerable voltage limits should be obtained from the specific equipment manufacturers. Table 1 summarizes some typical critical voltage levels when performing a motor-starting study and the effects of voltage dips (i.e., for information only, refer to NEMA MG1, NEMA ICS 1, NEMA ICS 2, UL 347, NEMA ICS 4, NEMA ICS 6, and specific equipment manufacturer for more details).

Table 1—Summary of representative critical system voltage levels when starting motors

Voltage drop location or problem	Minimum allowable voltage (% rated)
System voltage	95% to 105%
At terminals of starting motor	80%
All terminals of other motors that must reaccelerate	70%
AC contactor pick-up (by standard)	85%
DC contactor pick-up (by standard)	80%
Contactor hold-in (average of those in use)	60% to 70%
Solid-state control devices	90%

A motor-starting study can expose and identify the extent of a voltage drop problem. The voltage at each bus in the system can, for example, be readily determined by a computer study. Equipment locations likely to experience difficulty during motor starting can be immediately determined. In situations where a variety of equipment voltage ratings are available, the correct rating for the application can be selected. Circuit changes, such as off-nominal tap settings for distribution transformers and larger-than-standard conductor-sized cable, can also be readily evaluated. On a complex power system, this type of detailed analysis is very difficult to accomplish with time-consuming hand-solution methods.

Several methods of minimizing voltage dip on starting motors are based on the fact that during starting time, a motor draws an inrush current directly proportional to terminal voltage; therefore, a lower voltage causes the motor to require less current, thereby reducing the voltage dip.

Autotransformer starters are a very effective means of obtaining a reduced voltage during starting with standard taps ranging from 50% to 80% of normal rated voltage. A motor-starting study is used to select the proper voltage tap and the lower line current inrush for the electrical power system during motor start. Other special reduced-voltage starting methods include resistor, reactor, partial-winding, and wye-delta (Y-Δ). All starting methods are examined by an appropriate motor-starting study, and the best method for the particular application involved can be selected. In all reduced-voltage starting methods, torque available for accelerating the load is a very critical consideration once bus voltage levels are judged otherwise acceptable. Only 25% torque is available, for example, with 50% of rated voltage applied at the motor terminals. Any problems associated with reduced starting torque imposed by special starting methods are automatically uncovered by a motor-starting study.

Another method of reducing high inrush currents is by using a capacitor starting system (see Harbaugh and Ponsting [B16]). This maintains acceptable voltage levels throughout the system. With this method, the high inductive component of normal reactive starting current is offset by the addition, during the starting period only, of capacitors to the motor bus. This differs from the practice of applying capacitors for running motor power factor correction. A motor-starting study can provide information to allow optimum sizing of the starting capacitors and determination of the length of time the capacitor must be energized. The study can also establish whether the capacitor and motor can be switched together, or because of an excessive voltage drop that might result from the impact of capacitor transient charging current when added to the motor inrush current, the capacitor must be energized momentarily ahead of the motor. The switching procedure can appreciably affect the cost of final installation.

Use of special starters or capacitors to minimize voltage dips can be an expensive method of maintaining voltage at acceptable levels (see Harbaugh and Ponsting [B16]). Where possible, off-nominal tap settings for distribution transformers are an effective, economical solution for voltage dips. By raising no-load voltage in areas of the system experiencing difficulties during motor starting, the effect of the voltage dip can often be minimized. In combination with a load flow study, a motor-starting study can provide information to assist in selecting proper taps and help ensure that light load voltages are not excessively high.

The motor-starting study can be used to prove the effectiveness of several other solutions to the voltage dip problem as well. With a wound rotor motor, differing values of resistance are inserted into the motor circuit at various times during the starting interval to reduce maximum inrush (and accordingly starting torque) to some desired value. Figure 9 shows typical speed–torque characteristic curves for a wound rotor motor. With appropriate switching times (dependent on motor speed) of resistance values, practically any desired speed–torque (starting) characteristic can be obtained. A motor-starting study aids in choosing optimum current and torque values for a wound rotor motor application whether resistances are switched in steps by timing relays or continuously adjusted values obtained through a liquid rheostat feedback starting control.

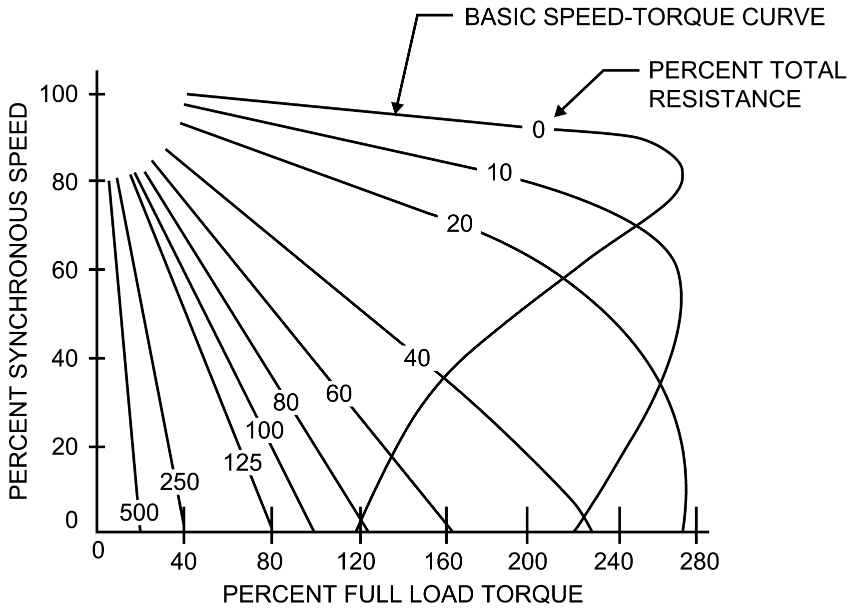


Figure 9—Typical wound rotor motor speed–torque characteristics

Motors with a specified lower-than-normal inrush characteristic can be used to manage applications in which the disturbance caused by motor starting is otherwise problematic. While more expensive than standard motors, the premium cost of so-called "low inrush" motors may offset the costs of other solutions to the voltage disturbance problem. These motors maintain nearly the same speed–torque characteristics as standard machines, but the inrush current is limited (usually to about 4.6 times full-load current compared with 6 times full-load current for a standard motor). Low-inrush motors are commonly used in applications where the electrical energy is supplied from local generators such as shipboard systems.

6.4 Weak source generation

6.4.1 Overview

Smaller power systems are usually served by limited capacity sources, which generally magnify voltage drop problems on motor starting, especially when large motors are involved. Small systems can also have on-site generation, which causes an additional voltage drop due to the relatively higher impedance of the local generators during the motor-starting interval. The type of voltage regulator system applied with the generators can dramatically influence motor starting as illustrated in Figure 10. A motor-starting study can be useful, even for analyzing the performance of small systems. Certain computer programs can accurately model generator transient behavior and exciter/regulator response under motor-starting conditions, providing meaningful results and conclusions.

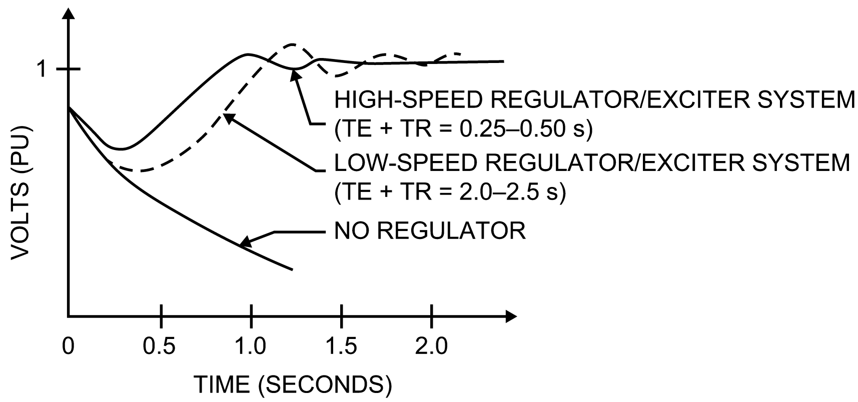


Figure 10—Typical generator terminal voltage characteristics for various exciter/regulator system; TE = exciter time constant (in seconds), TR = regulator input filter time constant (in seconds)

6.4.2 Special torque requirements

Sometimes special loads must be accelerated under carefully controlled conditions without exceeding specified torque limitations of the equipment. An example of this is starting a motor connected to a load through gearing. This application requires a special period of low-torque cushioned acceleration to allow slack in the gears and couplings to be picked up without damage to the equipment. Certain computer-aided motor-starting studies allow an instant-by-instant shaft output torque tabulation for comparison to allowable torque limits of the equipment. This study can be used for selecting a motor or a starting method, or both, with optimum speed–torque characteristics for the application. The results of a detailed study are used for sizing the starting resistors for a wound rotor motor, or in analyzing rheostatic control for a starting wound rotor motor that might be used in a cushioned starting application involving mechanical gearing or a coupling system that has torque transmitting limitations. High-inertia loads increase motor-starting time, and heating in the motor due to high currents drawn during starting can be intolerable. A computer-aided motor-starting study allows accurate values of motor current and time during acceleration to be calculated. This makes it possible to determine if thermal limits of standard motors will be exceeded for longer than normal starting intervals.

Other loads have special starting torque requirements or accelerating-time limits that require special high-starting torque (and inrush) motors. Additionally, the starting torque of the load or process may not permit low inrush motors in situations where these motors might reduce the voltage dip caused by starting a motor having standard inrush characteristics. A simple inspection of the motor and load speed–torque curves is not sufficient to determine whether such problems exist. This is another area where the motor torque and accelerating-time study can be useful.

7. Methodology and standards

7.1 Overview

From the previous discussion, it is apparent that, depending on the factors of concern in any specific motor-starting situation, more than one type of motor-starting study can be required.

7.2 Overall approach

7.2.1 The voltage drop snapshot

One method of examining the effect of voltage dip during motor starting is to ensure the maximum instantaneous drop that occurs leaves bus voltages at acceptable levels throughout the system. This is done by examining the power system that corresponds to the worst-case voltage. Through appropriate system modeling, this study can be performed by various calculating methods using a computer. The so-called "voltage drop snapshot study" (i.e., static motor study) is useful only for finding system voltages. Except for the recognition of generator transient impedances when appropriate, machine inertias, load characteristics, and other transient effects are usually ignored. This type of study, while certainly an approximation, is often sufficient for many applications.

7.2.2 The detailed voltage profile

This type of study allows a more exact examination of the voltage drop situation. Regulator response, exciter operation, and sometimes governor action are modeled to accurately represent transient behavior of local generators. This type of study is a simplified dynamic analysis and can be considered a series of voltage snapshots throughout the motor-starting interval.

7.2.3 The speed–torque and acceleration-time study

Perhaps the most in-depth analysis to perform motor-starting study is the speed–torque analysis and evaluation. Similar to a dynamic analysis discussed above, speed–torque evaluation provides accelerating torque for specified time intervals during the motor-starting period. Motor slip, load and motor torque, terminal voltage magnitude and angle, and the complex value of the motor current are values to be examined at the beginning of the simulation ($t = 0$) and at the end of each time interval.

Under certain circumstances, even across-the-line starting, the motor may not be able to break away from standstill, or it may stall at some speed before acceleration is complete. A speed–torque analysis, especially when performed using a computer program, and possibly in combination with one or more previously discussed studies, can predict these problem areas and allow corrections to be made before difficulties arise. When special starting techniques are necessary, such as with an autotransformer, speed–torque analysis can account for the autotransformer magnetizing current, and it can determine the optimum time to switch the transformer out of the circuit. The starting performance of wound rotor motors is examined through this type of study.

7.3 Mathematical relationships and hand calculations

7.3.1 Overview

There are basically three ways to solve for bus voltages realized throughout the system on motor starting. Regardless of the type of study required, a basic voltage drop calculation is always involved. When voltage drop is the only concern, the end product is this calculation when all system impedances are at maximum value and all voltage sources are at minimum expected level. In a more complex motor speed–torque and accelerating-time study, several voltage drop calculations are required. These are performed at regular time intervals following the initial impact of the motor-starting event and take into account variations in system impedances and voltage sources. Results of each iterative voltage drop calculation are used to calculate output torque, which depends on the voltage at machine terminals and motor speed. Since the interval of

motor starting usually ranges from a few seconds to 10 or more seconds, effects of generator voltage regulator and governor action are evident. Certain types of motor-starting studies account for generator voltage regulator action while a dynamic study is usually required in cases where other transient effects are considered important. A summary of fundamental equations used in various types of motor-starting studies follows in this subclause, along with examples illustrating applications of fundamental equations to actual problems, including typical computer program outputs.

7.3.2 Short-circuit/impedance method

This method involves reduction of the system to a simple voltage divider network (see Manning [B31]), as shown in Figure 11, where voltage at any point (bus) in a circuit is found by taking known voltage (source bus) multiplied by the ratio of impedance to the point in question over total circuit impedance. For the circuit of Figure 11:

$$V = E\frac{X_2}{X_1 + X_2} \tag{5}$$

or, more generally in terms of Z impedance (R + jX):

$$V = E\frac{Z_2}{Z_1 + Z_2} \tag{6}$$

where

E	is source voltage
V	is motor terminal voltage
Z_1	is system impedance
Z_2	is motor internal impedance

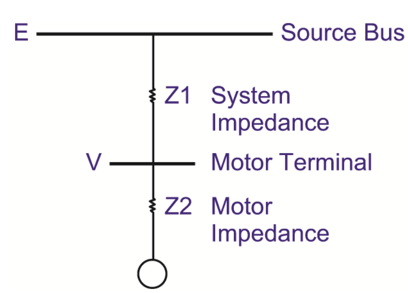


Figure 11 —Simplified impedance diagram

During motor starting, motor locked-rotor impedance for three-phase is used and calculated as:

$$Z_{LR} = \frac{V\text{rated voltage}_{L-L}}{(\sqrt{3}\ \ LRA)}\quad \Omega \tag{7}$$

Consequently, this value can be replaced with Z_2 in Equation (6) to calculate motor terminal voltage. The per unit of Z_{LR} is equal to the inverse of the inrush multiplier on the motor-rated kVA base:

$$Z_{LR} = \frac{1}{\left(\frac{LRA}{FLA}\right)} \quad \text{in per unit (p.u.)} \tag{8}$$

where

Z_{LR} is locked-rotor impedance, p.u.

LRA is locked-rotor current at rated voltage

FLA is motor full rated current

Since a starting motor is accurately represented as a constant impedance, the impedance method is a very convenient and acceptable means of calculating system bus voltages during motor starting. Validity of the impedance method can be seen and is usually used for working hand calculations. Where other than simple radial systems are involved, the computer greatly aids in obtaining necessary network reduction. Various system impedance elements must be represented as complex quantities, rather than as simple reactances, in order to obtain accuracy.

Representation used for the motor in any solution method for calculating voltage drop must be modified to reflect the lower inrush current. Some type of reduced-voltage starting is often used to minimize motor inrush current and thus reduce total voltage drop when the associated reduction in torque accompanying this starting method is permissible. This topic is discussed in different sections in more detail.

7.3.3 Current method

In general, in order to calculate any bus voltage in the system represented in Figure 12, the basic equations for the current method are as follows:

$$I_{per\ unit} = \frac{MVA_{load}}{MVA_{base}} \text{ at 1.0 per unit voltage} \tag{9}$$

$$V_{drop} = I_{per\ unit} \times Z_{per\ unit} \tag{10}$$

$$V_{bus} = V_{source} - V_{drop} \tag{11}$$

where

$Z_{per\ unit}$ is the total impedance between source bus and the load bus (p.u.)

V_{drop} is the voltage drop across the impedance (p.u.)

V_{bus} is the voltage at a specific bus (p.u.)

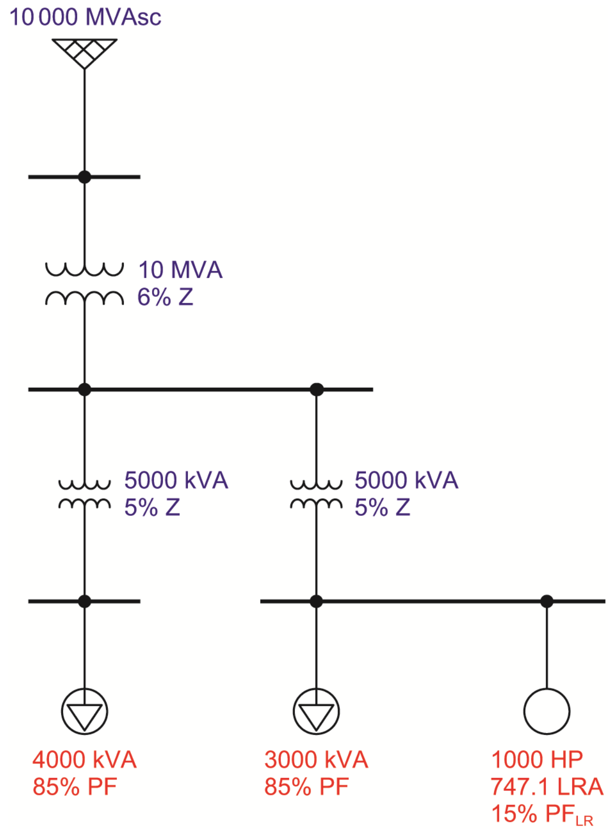


Figure 12—Typical single-line diagram

The impedance single-line diagram of Figure 12 is shown in Figure 13. For simplicity, the source (Bus1, connected at grid) impedance is assumed to be very small and is neglected.

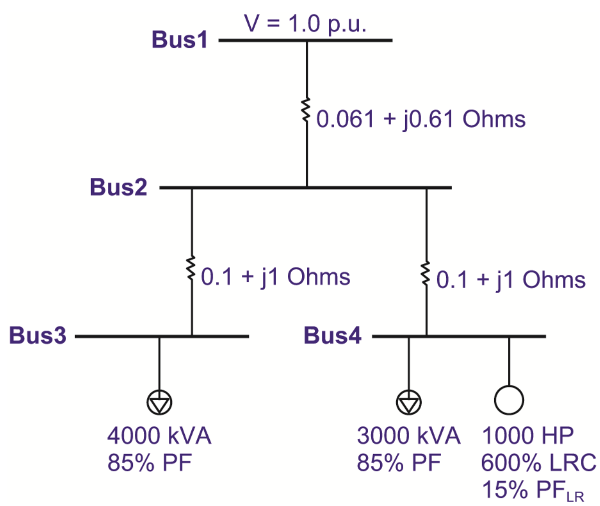


Figure 13—Impedance diagram for system in Figure 12

The quantities involved should be expressed in complex form for greatest accuracy, although reasonable results can be obtained by using magnitudes only for first-order approximations.

The disadvantage of this method is that, since all loads are not of constant current type, the current to each load varies as voltage changes. An iterative type solution procedure is, therefore, necessary to solve for the ultimate voltage at every bus, and such tedious computations are readily handled by a computer.

Notes:

- For a simplified approach, resistance components can be neglected.
- Use normal bus voltage as base kV and interpret the results accordingly.
- System (i.e., source) voltage should be minimum; assume 95% if it is not known.
- System impedance should be the highest as possible (i.e., based on the lowest short-circuit level available at the bus).
- Include voltage drop caused by running motors for all detailed calculations.
- For transformer impedance, include plus (+) standard tolerance (i.e., 7.5% for two-winding and 10% for three-winding).

7.3.4 Load flow solution method

From the way loads and other system elements are portrayed in Figure 14, it appears that bus voltages and the voltage dip could be determined by a conventional load flow program. This is true, by modeling the starting motor as a constant impedance load, and consequently, the load flow calculations yield the bus voltages during starting.

The basic equations involved in this process are repeated here (see Neuenswander [B40] and Stagg and El-Abiad [B44] for more information).

$$I_k = \frac{P_k - jQ_k}{V_k^*} - Y_k V_k \tag{12}$$

$$V_k = V_{ref} + \sum_{i=1}^{n} Z_{ki} \left(\frac{P_i - jQ_i}{V_i^*} - Y_i V_i \right) \tag{13}$$

where

I_k	is the current in the kth branch of any network
P_k	is the real power representative of the loads at the kth bus
Q_k	is the reactive power representative of the loads at the kth bus
V_k	is the voltage at the kth bus
Y_k	is the admittance to ground of bus k
V_{ref}	is the voltage of the swing or slack bus
n	is the number of buses in the network
Z_{ki}	is the system impedance between the kth and ith buses

The load flow solution to the motor-starting problem is very precise for finding bus voltages at the instant of maximum voltage drop. It is apparent from the expressions for I_k and V_k that this solution method is ideally

suited for the computer any time the system involves more than two or three buses. The load flow solution method for examining effects of motor starting allows a look at the voltage on the various system buses at a single point in time. The computer is used to solve several simultaneous equations that describe the voltage of each bus in a system at time zero and at the end of successive time intervals.

7.4 Generator reactance factors

Unless steady-state conditions exist, all of the above solution methods are valid for one particular instant and provide the single snapshot of system bus voltages as mentioned earlier. For steady-state conditions, it is assumed that generator voltage regulators have had time to increase field excitation sufficiently to maintain the desired generator terminal voltage. Accordingly, the presence of the internal impedance of any local generators connected to the system is ignored. During motor starting, however, the influence of machine dynamic behavior becomes important. To model the effect of a close-connected generator on the maximum voltage drop during motor starting requires inclusion of generator transient reactance (X_{d}') in series with other source reactances. In general, use of the transient reactance as the representation for the machine results in calculated bus voltages and, accordingly, voltage drops that are reasonably accurate. Both X' and X'' are impedances through the machine transient condition; however, X_{d}' compared with X'' has higher impedance value, and consequently, more conservative to use when performing motor-starting/voltage drop study.

Assuming, bus 1 in the system in Figure 14 is at the line terminals of a 12 MVA generator having 15% transient reactance (i.e., X_{d}' = 1.25 per unit on a 100 MVA base) rather than being an infinite source ahead of a constant impedance utility system, then, the transient impedance of the generator will be added to the system (i.e., assume the generator internal resistance is very small and is neglected).

The resulting impedance diagram is shown in Figure 14. Voltage at this new bus (bus99) is frequently referred to as a *voltage behind the transient reactance* which is actually the internal machine transient driving voltage (shown as *V*).

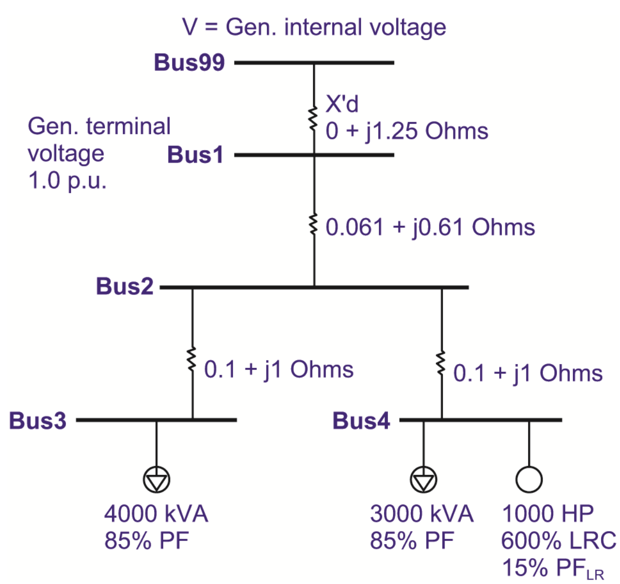


Figure 14—Revised impedance diagram showing transient reactance of a generator

When the steady-state operating voltage is 1.0 per unit (i.e., generator terminal voltage, $V_{terminal}$), the internal machine transient driving voltage can be considered the voltage that must be present ahead of the generator transient reactance with the terminal voltage maintained at 1.0 per unit during steady-state conditions while supplying power to the other loads on the system. The transient driving voltage V is calculated as follows:

$$V = V_{\mathrm{terminal}} + (\mathrm{j}X'_{\mathrm{d}})I_{load} \tag{14}$$

$$= 1.0 + (\mathrm{j}X'_{\mathrm{d}})I_{load} \tag{15}$$

where

$$V_{\mathrm{terminal}} = 1.0 \text{ per unit} \tag{16}$$

$$I_{load} = \frac{MVA_{load}}{MVA_{base}} \text{per unit} \tag{17}$$

Treatment of a locally-connected generator is equally applicable to all three solution methods described previously in 7.3. Such an approach cannot give any detail regarding the response of the generator voltage regulator or changes in machine characteristics with time. For a more detailed solution that considers time-dependent effects of machine impedance and voltage regulator action, the appropriate impedance and voltage terms in each expression must be continuously altered to accurately reflect changes that occur in the circuit. This procedure is also applicable to any solution methods considered. Figure 15 shows a simplified representation of the machine parameters that must be repeatedly modified to obtain the correct solution.

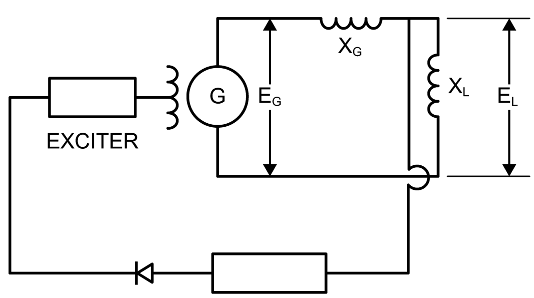


Figure 15 —Simplified representation of generator exciter/regulator system

$$E_L = E_G \frac{X_L}{X_L + X_G} \tag{18}$$

where

X_G varies with time as $X''_{\mathrm{d}} \rightarrow X'_{\mathrm{d}} \rightarrow X_{\mathrm{d}}$

E_G varies with time as $T''_{\mathrm{do}} \rightarrow T'_{\mathrm{do}} \rightarrow T_{\mathrm{do}}$ depending on exciter/regulator output

E_L is voltage across connected load

E_G is internal generator voltage

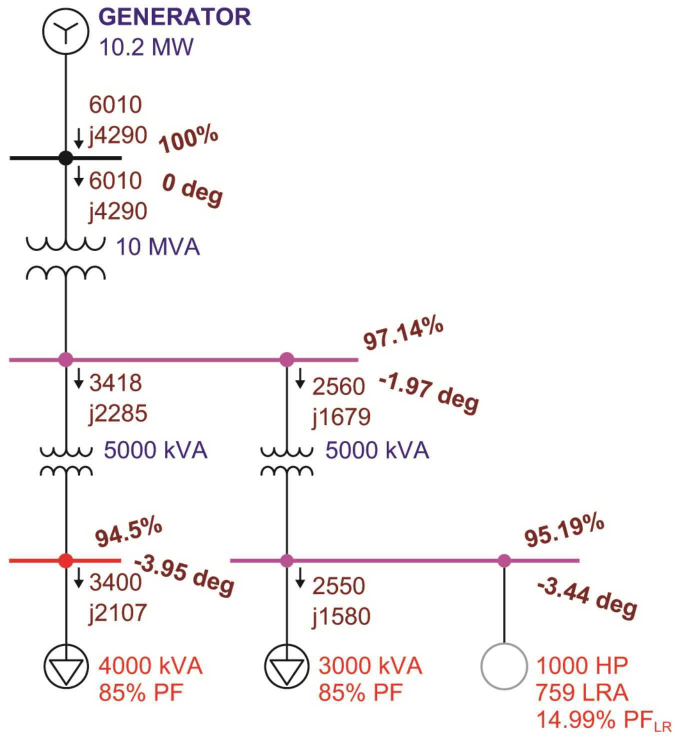
X_G is internal generator reactance

X_L is load reactance

7.5 Simple voltage drop simulation

To illustrate this type of analysis utilizing computer simulation, the system in Figure 15 is considered. Prior to starting, when steady-state load conditions exist, the impedance diagram shown in this figure applies with the motor offline. Note that the internal machine transient driving voltage *V* is typically done in the background and only the generator terminal voltage will show in a single-line diagram, see Figure 16(a). In general, generator terminal voltage is provided and considered as a design input data.

The computer output report of the steady-state load flow results for this case are shown both graphically and in tabular form in Figure 16(a) and Figure 16(b), respectively. All system loads are on-line, except the 1000 HP motor. The two non-motor loads are modeled as constant power type loads. The 12 MVA generator must supply steady-state power equal to 6.010 + j4.290 (MW + jMvar) as noted in Figure 16(a). The two loads combined require 5.95 + j3.687. Therefore, the losses in the system, including those through the generator, are equal to 0.06 + j0.603. With these values of power flowing during steady-state, prior to motor starting, the swing bus is at the required value of 1.0 p.u. voltage. The voltage drop at the motor bus, without the motor on line, is 4.81%, resulting in an operating voltage prior to starting of 0.9519 p.u. voltage.



(a)

LOAD FLOW REPORT @ T = 0.000-

Bus		Voltage		Generation		Load		Load Flow					XFMR
ID	kV	% Mag.	Ang.	MW	Mvar	MW	Mvar	ID	MW	Mvar	Amp	% F	% Tap
5 MVA XFMR SEC	4.160	94.502	-3.9	0	0	3.400	2.107	MAIN XFMR SEC	-3.400	-2.107	587.4	85.0	
MAIN XFMR SEC	13.800	97.137	-2.0	0	0	0	0	SWING	-5.978	-3.965	308.9	83.3	
								5 MVA XFMR SEC	3.418	2.285	177.1	83.1	
								MTR START BUS	2.560	1.679	131.9	83.6	
MTR START BUS	4.160	95.186	-3.4	0	0	2.550	1.580	MAIN XFMR SEC	-2.550	-1.580	437.4	85.0	
*SWING	115.000	100.000	0.0	0	0	0	0	MAIN XFMR SEC	6.010	4.290	37.1	81.4	
								GENERATOR	-6.010	-4.290	37.1	81.4	
*GENERATOR	115.000	105.880	4.0	6.034	4.972	0	0	SWING	6.034	4.972	37.1	77.2	

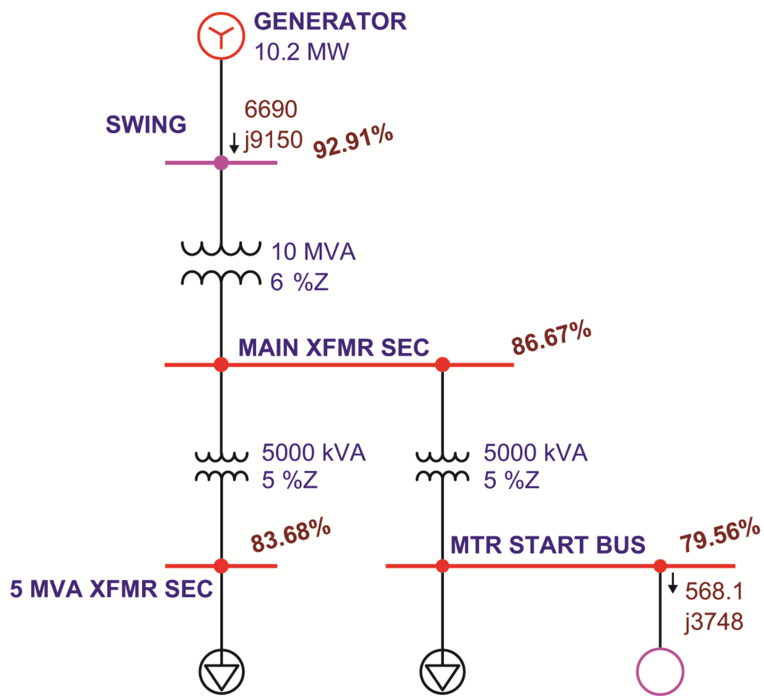
* Indicates a voltage regulated bus (voltage-controlled or swing type machine connected to it).

(b)

Figure 16—(a) Computer-generated graphical output format: steady-state; (b) Computer-generated tabular output format: steady-state

For convenience, the voltage angle associated with the generator (or swing) bus is assumed to be zero, which results in the corresponding shift for all other bus voltages. Since the transformers are connected delta-delta, the angular phase shifts indicated are due to the voltage drops alone.

It can be seen from the computer simulation output report, shown graphically and in tabular form Figure 17(a) and Figure 17(b), that when the 1000 HP motor starts, the voltage at the motor-starting bus is dropped to about 0.795 p.u. with –5.3° angle. Although this voltage is close to the value required to start many motors, it may be below for proper operation of other equipment like ac control devices that may be connected to these motor-starting buses. Further examination of this problem shows that when the motor-starting period is over and the motor is in operation, the voltage at the motor bus recovers to 0.939 p.u. A second study could be easily performed to explore the effects of increasing the motor-starting bus voltage by adjusting the transformer tap settings.



(a)

LOAD FLOW REPORT @ T = 1.000+

Bus		Voltage		Generation		Load		Load Flow					XFMR
ID	kV	% Mag.	Ang.	MW	Mvar	MW	Mvar	ID	MW	Mvar	Amp	% PF	% Tap
5 MVA XFMR SEC	4.160	83.682	-5.6	0	0	3.400	2.107	MAIN XFMR SEC	-3.400	-2.107	663.4	85.0	
MAIN XFMR SEC	13.800	86.675	-3.1	0	0	0	0	SWING	-6.601	-8.262	510.4	62.4	
								5 MVA XFMR SEC	3.423	2.334	200.0	82.6	
								MTR START BUS	3.178	5.927	324.6	47.3	
MTR START BUS	4.160	79.561	-5.3	0	0	3.118	5.328	MAIN XFMR SEC	-3.118	-5.328	1076.9	50.5	
*SWING	115.000	92.905	-0.7	0	0	0	0	MAIN XFMR SEC	6.690	9.150	61.3	59.0	
								GENERATOR	-6.690	-9.150	61.3	59.0	
*GENERATOR	115.000	105.880	4.0	6.755	11.011	0	0	SWING	6.755	11.011	61.3	52.3	

* Indicates a voltage regulated bus (voltage-controlled or swing type machine connected to it).

(b)

Figure 17 —(a) Computer-generated graphical output format: motor starting; (b) Computer-generated tabular output format: steady-state

7.6 Motor-acceleration time

When a detailed motor speed–torque and starting time are required, the following equations can be used (see Weidmer and Sells [B47]). The equations, in general, apply to both induction and synchronous motors since the latter behave almost exactly as do induction machines during the starting period.

A simplified approximation for starting time (in seconds) is:

$$t(s) = \frac{WR^2 (r/\min_1 - r/\min_2)(2\pi)}{60\, g\, T_n} \tag{19}$$

where

t	is the time in seconds to accelerate (i.e., motor-acceleration time)
WR^2	is the inertia
g	is the acceleration due to gravity
T_n	is the net average accelerating torque between $\mathrm{r/min}_1$ and $\mathrm{r/min}_2$ (i.e., RPM_1 and RPM_2)

Substituting for g and rearranging yields:

$$t(s) = \frac{\mathrm{Wk}^2 \left(\mathrm{r/min}_1 - \mathrm{r/min}_2\right)(2\pi)}{60 g T_n} \tag{20}$$

Also, the instantaneous torque equation is as follows (see Beeman [B3]; Fitzgerald, Kingsley, and Kusko [B15]; and Peterson [B42]):

$$T = \frac{q_1\, V^2\, (r_2/s)}{\omega_s\, (r_1 + r_2/s)^2 + (X_1 + X_2)^2} \tag{21}$$

where

T	is the instantaneous torque
ω_s	is the angular velocity at synchronous speed
$(r_1 + \mathrm{j}X_1)$	is the stator equivalent impedance
$(r_2/\mathrm{s} + \mathrm{j}X_2)$	is the rotor equivalent impedance
q_1	is the number of stator phases (3 for a 3-phase machine)
V	is the motor terminal voltage

A simplified sample problem is presented for solution by hand. In this way, it is possible to appreciate how the computer aids in solving the more complex problems. A typical motor and load speed–torque characteristic curve is shown in Figure 18.

Assuming:

- Motor HP = 1000 (induction motor)
- Motor r/min = 1800
- T_n (T_{net}) = 3954.92 N-m (2917 lb-ft) (at FLA), see Equation (1)
- Motor inertia WR^2 = 11.377 kg-m^2 or 270 lb-ft^2
- Load inertia WR^2 = 34.133 kg-m^2 or 810 lb-ft^2

It is also possible to find the average value for accelerating torque over the time interval defined by each speed change. This can be done graphically for hand calculations and the results are tabulated in Table 2.

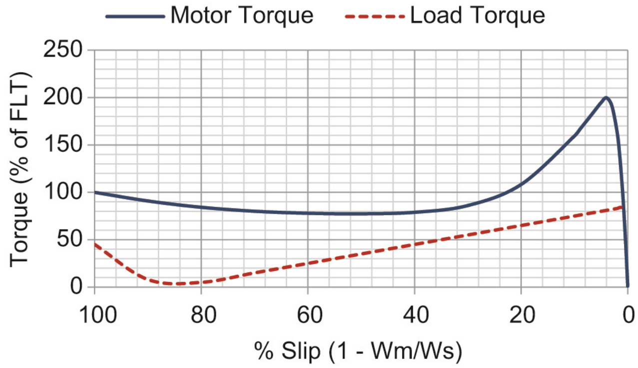


Figure 18—Typical motor and load torque–slip characteristics

Table 2—Average values for accelerating torque over time interval defined by a speed change

Speed	T_{motor}	T_{load}	T_{net}	T_{net} lb-ft
0%	100%	30%	—	—
—	—	—	77.5%	2260
25%	120%	35%	—	—
—	—	—	100%	2917
50%	160%	45%		—
—	—	—	120%	3500
75%	190%	65%	—	—
—	—	—	62.5%	1823
95%	80%	80%	—	0.0

Applying the simplified Equation (20) for the starting time provided earlier:

$$t_{0-25} = \frac{(270+810)(450-0)}{(308)(2260)} = 0.6981\ \text{s}$$

$$t_{25-50} = \frac{(1080)(900-450)}{(308)(2917)} = 0.5410\ \text{s}$$

$$t_{50-75} = \frac{(1080)(1350-900)}{(308)(3500)} = 0.4580\ \text{s}$$

$$t_{75-95} = \frac{(1080)(1710-1350)}{(308)(1823)} = 0.6925\ \text{s}$$

The total time to 95% of synchronous speed is the sum of the times for each interval, or approximately 2.38 s (i.e., motor-starting time).

The current drawn during various starting intervals can be obtained from a speed–current curve, such as the typical one shown in Figure 19. This example has assumed full voltage available to the motor terminals, which is an inaccurate assumption in most cases. Actual voltage available can be calculated at each time interval. The accelerating torque will then change by the square of the calculated voltage. This process can be performed by graphically plotting a reduced-voltage speed–torque curve proportional to the voltage calculated at each time interval, but this becomes tedious in a hand calculation.

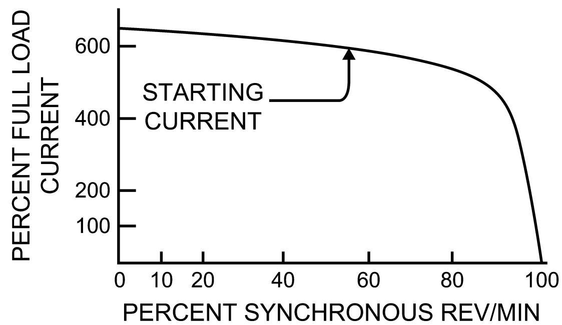


Figure 19 —Typical motor speed–current characteristic

More accurate results are possible with computer program analysis. Figure 20 is a computer combined output of motor-starting voltage and motor slip as function of time for a 1000 HP motor in Figure 17(a). The motor is started 1 s into the simulation and took about 3.6 s to fully start (i.e., motor-acceleration time). The voltage at the motor-starting bus prior to starting the motor is 0.951 p.u.; however, the voltage at the motor-starting bus drops to about 0.795 p.u. at the instant the motor starts.

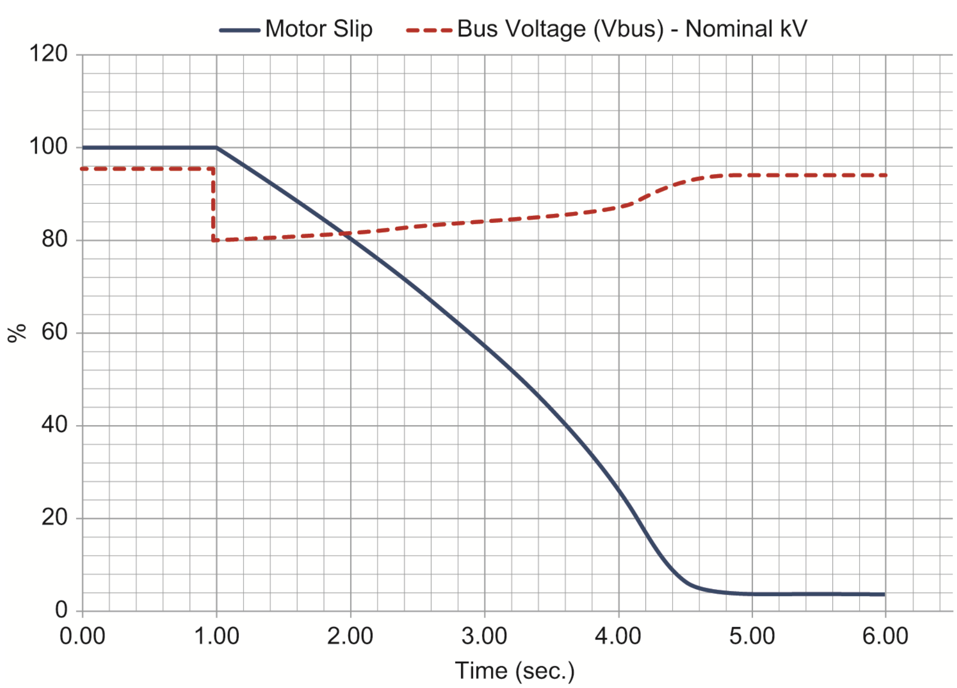


Figure 20 —Computer-generated plot: motor slip and bus voltage

7.7 Computer-based calculations

7.7.1 Overview

During the motor-starting period, the starting motor appears to the system as small impedance connected to a bus. It draws a large current from the system, typically six times the motor-rated or full-load current. This large current draw, therefore, results in voltage drops in the system and imposes disturbances to the normal operation of other system loads. Since the motor-acceleration torque depends on motor terminal voltage, in some cases the starting motor may not be able to reach its rated speed due to extremely low terminal voltage. This makes it necessary to perform a motor-starting analysis. The purpose of performing a motor-starting study is twofold: to investigate whether the starting motor can be successfully started under the operating conditions, and to see if starting the motor will seriously impede the normal operation of other loads in the system.

The excessive current not only causes higher voltage drop and long acceleration time, but can also result in the following:

- For starting motors: reduced starting torque (torque varies as the voltage squared) might not be sufficient to accelerate the load or might damage the rotor due to heating
- For running motors: load torque might exceed the motor breakdown torque for squirrel-cage induction motors and pull-out torque for synchronous motors
- Voltage-sensitive devices, such as drives, will drop out if voltage drop exceeds 15%

The following steps are recommended during the initial design stage:

- Perform voltage drop calculations or a system study if one of the following conditions is present:
  - Motor horsepower (or kW) is greater than 30% of the transformer bank kVA rating
  - Fault level at the motor bus is less than six times motor-starting inrush
  - Motor horsepower (or kW) exceeds 10% to 15% of the generator rating
- Evaluate the impact on voltage-sensitive loads if the voltage drop due to motor starting exceeds 12% to 15%.
- Perform detailed calculations, taking into account the resistance components and initial load if the voltage drop is 15% or higher. This should be carried out as a part of the system study, using power system analysis software.
- Check motor performance during acceleration for motors driving high-inertia loads or if acceleration time is close to, or exceeds, the motor hot-stall time. Motor performance curves can be generated by the motor designer and shall be specified in the request for bids.

Using commercially available off-the-shelf software (COTS), motor-starting studies can be carried out using four main modeling techniques to determine the voltage drop and acceleration time of single or multiple motors. A detailed comparison of these models is covered in Table 3.

- Static motor-starting model (non-dynamic motor model)
- Characteristic curve motor-starting model
- Dynamic motor-starting model (dynamic motor model only)
- Full dynamic motor-acceleration model (motor and generator dynamics)

7.7.2 Static motor starting

In the static motor-starting method, it is assumed that the starting motor can always be started and the motor-starting duration is given. During the starting period, the motor is represented by its locked-rotor impedance, which draws the maximum possible current from the system and has the most severe effect on the system. Once the starting period has passed, the starting motor is changed to a constant kVA load.

Static motor-starting method is a recommended approach under any of the following conditions:

- New system conceptual design
- Motor and connected load dynamics are unavailable and cannot be estimated
- Acceleration times of the motors are not required to be calculated
- Objective is to determine the voltage impact on buses to size feeders and/or check protection settings
- Accelerating motors are primarily low-voltage motors
- Motors are connected to a system fed by utility grid(s) only
- Motors are connected to a system fed by generator(s) only, but the size of the starting motor is less 10% of the generator kVA rating

This method is suitable for checking the effect of motor starting on the system when the dynamic model is not available for starting motors. The static motor-starting calculation method involves:

- Time domain using a static model
- Switching motors modeled as Z_{LR} during starting and constant kVA load after starting
- Running load flow when any change in system

7.7.3 Characteristic curve motor starting

In the characteristic curve motor-starting method, the starting motors are represented by the torque-slip curve (TSC) model, which is a steady-state model in nature. This study gives the worst system voltage profile as well as the motor-starting duration, and can also detect motor-starting failures. The motor circuit model can be defined as shown in Figure 21.

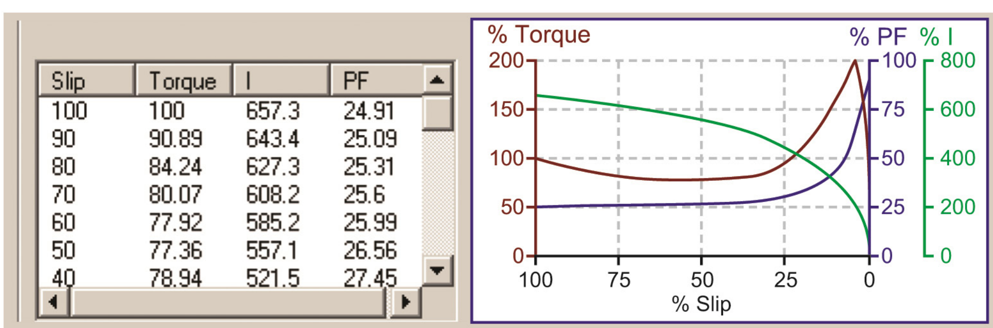


Figure 21 —Torque-slip characteristics using point form

7.7.4 Dynamic motor starting

In the dynamic motor-starting method, using motor circuit models, the entire dynamic model for the motor and connected load is used to simulate the acceleration behavior and voltage impact on the entire network. This method assumes the generator to be modeled as a constant voltage behind impedance. The motor circuit model can be defined in multiple ways, shown in Figure 22, Figure 23, and Figure 24:

a) Single-cage circuit model with or without deep-bar effect where stator and rotor resistances and reactances may change with speed

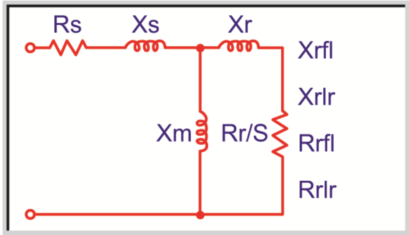


Figure 22 —Single-cage circuit model with deep-bar effect

b) Double-cage circuit model with integrated rotor cages

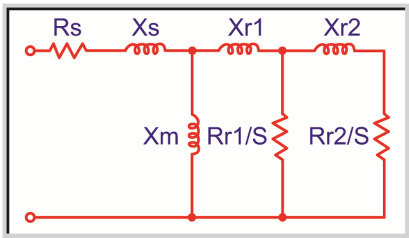


Figure 23 —Double-cage circuit model with integrated rotors

c) Double-cage circuit model, with independent rotor cages

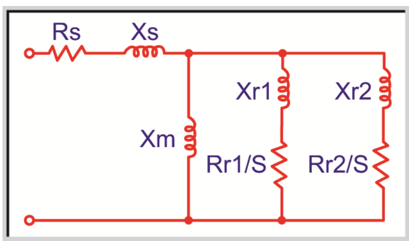


Figure 24 —Double-cage circuit model with independent rotor cages

Dynamic motor starting using a circuit model is a recommended approach under any of the following conditions:

- Existing system design change or expansion
- Motor and connected load dynamics are available and/or can be estimated
- Acceleration times of the motors are required to be calculated
- Accelerating motors are primarily medium-voltage motors
- Motors are connected to a system fed by generator(s), but the size of the starting motor is greater than 10% of the generator kVA rating

7.7.5 Full dynamic motor acceleration

In the full dynamic motor-acceleration calculation, the starting motors are represented by dynamic models and the generators are modeled with detailed exciter, governor, and stabilizer models to accurately account for effects of their responses to system impact due to motor starting. This method is used to determine if a motor can be started, and how much time is needed for the motor to reach its rated speed, as well as to determine the effect of voltage dips on the system.

Full dynamic motor-acceleration method involves:

- Time domain using dynamic model and inertia model
- Dynamic model used for the entire simulation
- Requires motor and load dynamic model

8. System simulation and modeling

8.1 Modeling of components in motor-starting studies

Since other loads on the system during motor starting affect the voltage available at the motor terminals, the information necessary for a load flow or short-circuit study is essentially the same as that required for a motor-starting study. Table 3 summarizes differences in the modeling techniques between these methods for major power system components.

With respect to utility ties, in general, it is applicable to use the rated voltage behind dynamic analysis reactance (X_{sc}) if there is insignificant difference between X' and X''.

Table 3—Component modeling in various methods

Element	Static motor starting	Characteristic curve motor starting	Dynamic motor starting	Full dynamic motor acceleration
Generators	Constant voltage behind X_d'	Constant voltage behind X_d'	Constant voltage behind X_d'	Dynamically modeled
Exciter/governors	Not modeled	Not modeled	Not modeled	Dynamically modeled
Utility ties	Constant voltage behind X_{sc}	Constant voltage behind X_{sc}	Constant voltage behind X_{sc}	Constant voltage behind X_{sc}
Large operating motors	Constant kVA	Constant kVA	Constant kVA	Dynamically modeled
Small operating motors	Constant kVA	Constant kVA	Constant kVA	Constant kVA
Starting motors	Locked-rotor Z, starting time	Torque-slip curve	Dynamically modeled	Dynamically modeled
Starting motors, post starting	Constant kVA	Constant kVA	Circuit model	Dynamically modeled
Starters	Modeled	Modeled	Modeled	Modeled
Transformer tap/load tap-changer (LTC)/voltage regulator/capacitor	Modeled	Modeled	Modeled	Modeled

The accelerating torque of the motor varies as a function of the motor terminal voltage, motor rotor current, and the motor speed. As the motor accelerates, both the current and the power factor change, affecting the terminal voltage. Therefore, in the motor-starting simulation, the following steps are used:

- Solve the power flow equations to get the terminal voltage at time t = 0.
- Assume an initial motor speed.
- Calculate the motor current, torque, and terminal voltage using the power flow and the equivalent circuit.
- Integrate the shaft dynamic equation to a new rotor speed.
- Calculate the slip and R2/slip terms.
- Increment the time step and repeat the entire calculations until the steady-state speed is reached.

In the motor-acceleration simulation, the following steps are used:

- Solve the power flow equations to get the terminal voltage at time t = 0.
- Determine the initial conditions of all dynamically-modeled machines.
- Integrate the dynamic equations of all motors and generators including the excitation and governor equations along with the shaft dynamic equation.
- Solve the new power flow equations at the end of each time step.
- Report the current, torque, slip, and terminal voltage of the starting motors.
- Increment the time step and repeat the entire calculations until the steady-state speed is reached.

Usually, the motor-starting analysis programs have a motor model library and a load model library. The user can select the available data or can edit the existing data to meet the data requirement. The load models are available for typical loads such as fans, pumps, compressors, blowers, and motor-generator set. During the simulation, the necessary parameters are monitored in order to assess the effectiveness of the motor starting.

Some of the parameters useful for the motor-starting evaluation are:

- Bus voltage (V_{bus})
- Motor speed
- Motor terminal voltage ($V_{terminal}$)
- Motor input current
- Motor torque
- Load torque
- Accelerating torque
- Real power and reactive power
- Power factor

8.2 Motor mechanical model

8.2.1 Motor characteristic curves

When matching an ac motor to the requirements of a specific load it is important to check the torque requirements of the load and the torque capabilities of the motor in addition to speed and horsepower.

The following examples discuss several ac motor and load-performance characteristics, such as breakdown torque, full-load torque, and slip. Many of the characteristics can be visualized by plotting them as a speed–torque curve, such as shown in Figure 25. This is the speed–torque curve for a typical NEMA B motor. For purposes of this discussion, assume it is a 10 HP, 1200 RPM ac squirrel-cage motor having a 61.011 N-m (45 lb-ft) full-load torque.

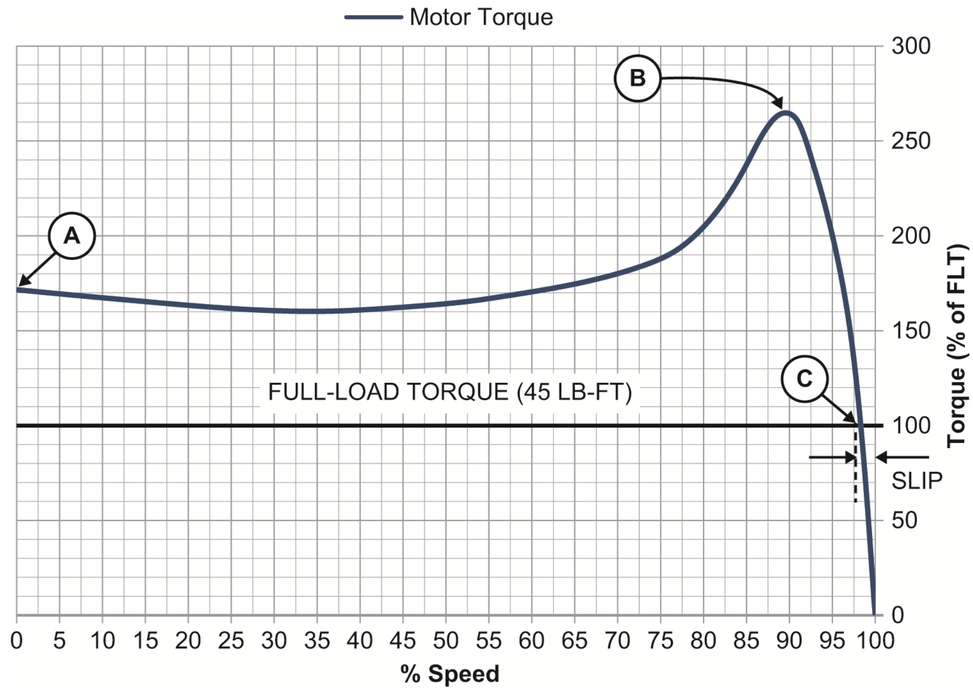


Figure 25 —Load–torque characteristics (sample 1)

Point A is the starting point inasmuch as the speed is zero. The torque must be the starting torque, which is 172% of full-load torque or, for our example motor, this torque is 104.94 N-m (77.4 lb-ft).

Moving to the right along the curve, we see that torque drops off a bit as the motor picks up speed until about 40% of synchronous speed is reached. At this point, the torque starts to increase and continues doing so until about 90% of speed is reached at point B. The motor now has reached the maximum or breakdown torque. Projecting an imaginary horizontal line to the torque scale, we see that breakdown torque is 265% of full-load torque or 162.69 N-m (120 lb-ft) at a speed of 1080 RPM.

From point B on, the torque decreases. At point C, the motor reaches the 100% torque line, which of course is full-load torque or 61.01 N-m (45 lb-ft) and is operating at its full-load speed or 1170 RPM.

Figure 26 shows the same motor speed–torque curve that has been discussed plus the speed–torque curves of two pieces of machinery. Curve (1) is the speed–torque curve of a loaded ball mill, and curve (2) is the curve of a loaded rolling mill. The objective is to see whether this motor is suitable for driving these two machines.

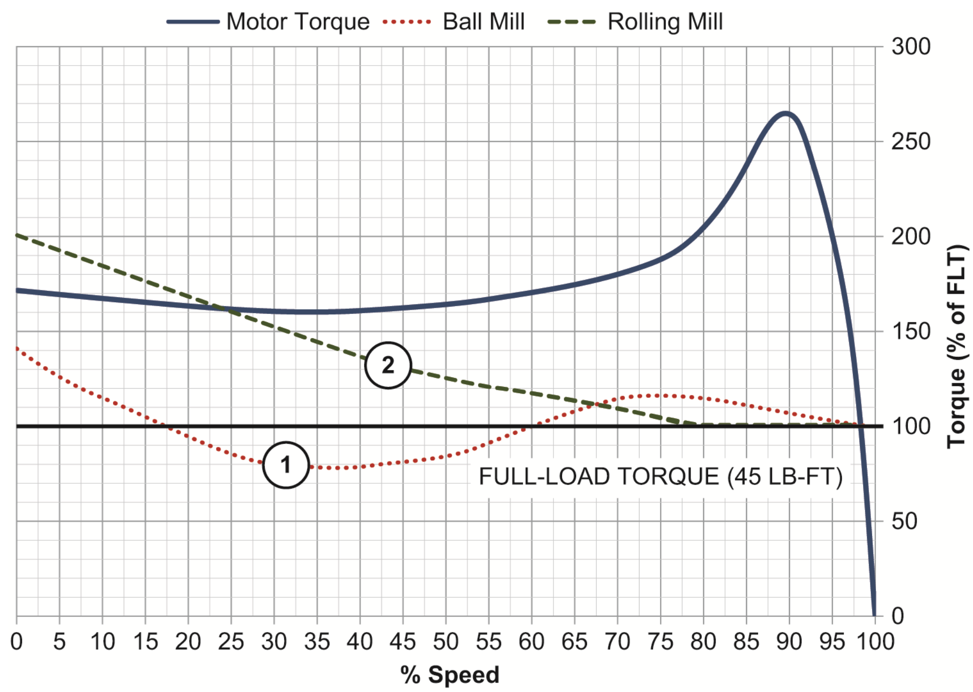


Figure 26 —Load-torque characteristics (sample 2); (1) loaded ball mill, (2) loaded rolling mill

Both machines require a full-load torque of 61.01 N-m (45 lb-ft) which is the same as the full-load torque produced by the motor. Going to the zero speed line next, we see that the ball machine (curve 1) requires a starting torque of about 140%, which is less than the 150% torque supplied by the motor. However, the voltage drop during the motor-starting condition and its impact on motor load–torque characteristic should be considered. Typically, motor manufacturers will provide load–torque characteristics for different voltage conditions, e.g., 80%, 100%, and 110%. It is obvious then that this motor produces enough torque to get the ball mill started. Examining the rest of the ball mill curve from zero to full-load speed, we see that all the torque values required are less than the torque values produced by the motor.

Now let’s look at the rolling mill (curve 2). Starting again at zero speed, we see that this machine requires a starting torque of 200%, which is greater than the motor’s starting torque of 150%.

Therefore, this particular motor cannot be used to operate this particular rolling mill. The dotted line speed–torque curve (2) in Figure 27 is for the same loaded rolling mill we just discussed. The dash line speed–torque curve (C), however, is for a 10 HP, 1200 RPM ac squirrel-cage motor of NEMA design C. Both the motor and the machine still have the same full-load torque of 61.01 N-m (45 lb-ft).

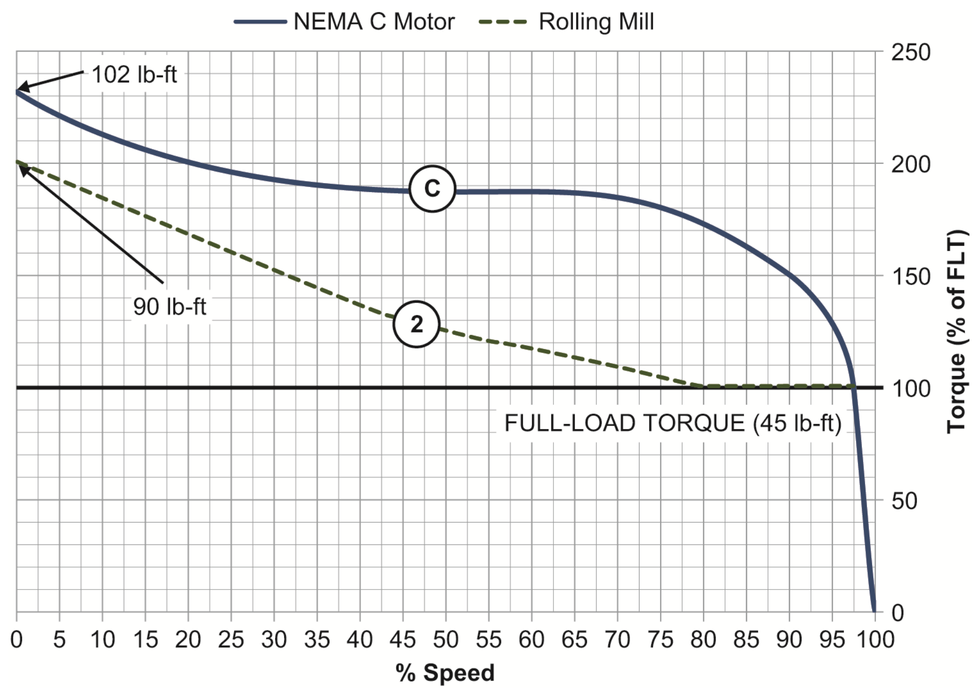


Figure 27 —Load–torque characteristics (sample 3)

In examining the starting point of these two curves, we see that the rolling mill (curve 2) still requires a 122.02 N-m (90 lb-ft) starting torque, but this motor produces a 138.29 N-m (102 lb-ft) starting torque. All other torque points of the rolling mill curve are less than the corresponding torque values produced by the motor. The NEMA design C motor will meet the requirements of the load.

8.2.2 Sensitivity of characteristic curves to resistance and reactance

Performance of a motor and connected load are determined by their three basic characteristics: speed, torque, and horsepower.

Some loads operate at a constant speed, while others require that their speed be varied. Some loads require a low starting torque, while others require a high starting torque. Similarly, motors can operate over a wide range of horsepower values necessary to drive the connected load.

It is not surprising to find that motors are manufactured in various designs to meet these requirements. Normally, the speed–torque characteristics of common ac squirrel-cage motors are altered by changing the resistance and/or reactance of the rotor bars. The resistance of a rotor bar can be increased by decreasing its cross-sectional area or by using a higher resistivity material, such as brass.

An increase in rotor bar resistance will tend to:

- Increase starting torque
- Lower starting current
- Lower full-load speed
- Lower efficiency
- Not affect breakdown torque

The reactance of a rotor bar can be increased by placing the conductor deeper in the rotor cylinder or by closing the slot at the air gap. Locating the conductor deeper in the iron positions it farther from the air gap.

An increase in rotor bar reactance will tend to:

— Lower starting torque
— Lower starting current
— Lower breakdown torque
— Not affect full-load conditions

As with most product engineering, the final design is usually a compromise. Therefore, a designer might lower full-load speed by increasing rotor bar resistance, and at the same time lower starting current by increasing rotor bar reactance.

8.2.3 Deep-bar effect

The deep-bar effect is the characteristic of induced current crowding toward the top of a rotor bar embedded in magnetic steel when exposed to an ac field. This results in an increase in the effective resistance of the rotor bar and change in the reactance.

When special motor applications are involved, such as high starting torque or low starting current, motor manufacturers may use special deep bar or double squirrel-cage motor rotor designs. These designs can be represented either by their torque/speed curves, or by an equivalent electrical circuit model with two (or more) parallel rotor branches represented. This increases the complexity of the equivalent circuit and the corresponding mathematical solution beyond that of the more simplified single-rotor model.

8.3 Motor inertia

The inertia of a load and its speed–torque characteristic determine the acceleration time required to bring the load up to speed. The acceleration time is directly proportional to the inertia (load plus motor) and is inversely proportional to the acceleration torque. If the acceleration torque produced by the motor is insufficient to bring the machine (load) to its operating speed within the permissible time, the motor may stall or even may suffer damage to the rotor. The inertia (i.e., or moment of inertia) is expressed as:

— WR^2 = J-kg-m^2 or lb-ft^2
— W = weight, kg or lb
— k or R = radius of gyration, m or ft

When the motor and the driven load run at different speeds, the load inertia at motor speed can be calculated using Equation (22).

$$WR^2_{Load} \text{ at motor rpm} = WR^2_{Load} \times \left(\frac{\text{load rpm}}{\text{motor rpm}} \right)^2 \tag{22}$$

High-inertia applications create thermal and mechanical impact. Machines that typically have inertia (referred to the motor shaft) greater than five times that of the motor rotor are considered to be a high-inertia load. However, the standard inertia tables given in NEMA MG1 should be used as a reference to determine the high-inertia loads (i.e., inertia greater than the one listed in these tables).

The normal-load inertia given in the standard is based on the formula:

$$\text{normal load } WK^2 = \mathrm{A} \times \left[\frac{\mathrm{hp}^{0.95}}{\left(\frac{\mathrm{rpm}}{1000}\right)^{2.4}} \right] - 0.0685 \times \left[\frac{\mathrm{hp}^{1.5}}{\left(\frac{\mathrm{rpm}}{1000}\right)^{1.8}} \right] \tag{23}$$

where

A is 24 for 300 rpm to 1800 rpm motors

A is 27 for 3600 rpm motors

For motors driving loads with high inertia or load torques, copper or copper alloy rotor bars are typically used. Double-cage rotors or rotors with deep rectangular or other shapes of bar design are used when high locked-rotor torque, low full-load slip, and low starting current are desired. The deep rotor-bar design used in two- and four-pole motor design has an added advantage over double-cage rotors for heat dissipation during starting and acceleration.

In addition, when a motor attempts to start, current flow within the motor results in a rise in internal temperature. The design of a motor is based on assumptions about the maximum temperature that should be experienced within the motor, which translates into a limitation in the number of attempts at starting that motor that can be allowed in a period of time. It is not unusual for commissioning of some mechanical systems (especially fans) to require numerous starts as the driven load is being balanced. These applications may require special controls that count the number of starts, and impose mandatory cooling periods between starts to prevent motor overheating.

8.4 Motor load model

Usually, the load model is presented in graphical form or in equation form. The data includes a model name, model type (graphical or equation), moment of inertia of the load, and the torque speed characteristics of the load. The models are generally available for loads such as fans, pumps, compressors, blowers, and motor generator set.

8.5 Basic assumptions

Besides using standard impedance values for transformers and cables, it is often necessary to use typical or assumed values for other variables when making motor-starting voltage drop calculations. This is particularly true when calculations are for evaluating a preliminary design and exact motor and load characteristics are unknown. Some common assumptions used in the absence of more precise data follow:

a) *Horsepower to kVA conversion*. A reasonable assumption is 1 HP equals 1 kVA. For synchronous motors with 0.8 leading, running power factor, and induction motors, it can easily be seen from Equation (24):

$$HP = \frac{kVA(PF)(EFF)}{0.746} \tag{24}$$

$$MF_{CL} = \frac{kVA_{LR}}{HP} \tag{25}$$

$$MF_{CL} = \frac{\sqrt{3} \times kV_{LL} \times LRC}{HP} \tag{26}$$

$$MF_{LR} = \frac{LRC}{FLA} \tag{27}$$

where

MF_{CL} is the multiplication factor based on NEMA Code Letter (see [B37])

MF_{LR} is the ratio of locked-rotor current (LRC) to FLA

LRC is the locked-rotor current

kV_{LL} is the line-to-line voltage

FLA is the full-load current (amp)

HP is the motor-rated output power in horsepower

The ratio of 0.746 to efficiency times the power factor approaches unity for most motors given the 1 HP/kVA approximation. Therefore, for synchronous motors operating at 1.0 PF, a reasonable assumption is 1 HP equals 0.8 kVA.

b) *Locked-rotor current*. Usually, a conservative multiplier for motor locked-rotor currents is obtained by assuming the motor to have a code G characteristic with locked-rotor current equal to approximately 6 times the full-load current with full voltage applied at motor terminals (see the National Electrical Code® [NEC®] [NFPA 70]). A conservative and acceptably-accurate method for determining the locked-rotor current to full-load running current ratio is to use the reciprocal of the motor's subtransient reactance when this characteristic is known.

If,

$$kVA \approx HP \tag{28}$$

Then,

$$MF_{CL} \approx MF_{LR} \tag{29}$$

c) *Starting power factor*. The power factor of a motor during starting determines the amount of reactive current that is drawn from the system, and thus, to a large extent, the maximum voltage drop. Typical data (see Beeman [B3]) suggest the following:

— Motors under 1000 HP, PF = 0.20

— Motors 1000 HP and over, PF = 0.15

The starting power factor can also be determined by knowing the short-circuit *X*/*R* ratio of the machine. Thus:

$$\text{Starting power factor} = \cos(\arctan X/R) \tag{30}$$

If a machine has an X''_d equal to 0.17 p.u. impedance on its own machine base, and a short-circuit *X/R* ratio of 5.0, then its locked-rotor current ratio would be 5.9 and associated starting power factor would be 20% or 0.2 p.u.

These power factor values are only rules of thumb for larger, integral horsepower-sized "standard" design motors. Actual motor power factors may vary dramatically from these values, especially for small size machines or any size special-purpose motor. For example, the starting power factor of a "standard" 5 horsepower motor may be 60% or larger, while the starting power factor of a high starting torque, fractional horsepower motor may be 85% or more. Wherever large numbers of small motors or any number of special torque characteristic motors are connected to a system or circuit, actual power factors should always be confirmed for purposes of performing accurate motor-starting calculations.

9. Motor-starting methods

9.1 Direct on-line (DOL)

A DOL start is the simplest, most common, and least expensive method of starting squirrel-cage induction and synchronous motors. Direct on-line starting offers high-acceleration torque and reduced acceleration time. However, the following criteria must be checked for large motors:

- The power system must be robust, and the voltage drop caused by direct on-line starting must not exceed flicker limits at all voltage levels.
- With synchronous motors, high accelerating and oscillating (pulsating) torque may be a problem for the driven equipment during starting. A torsional analysis is required for such applications.
- With squirrel-cage induction motors, high starting and breakdown torques may cause a shock for some types of driven equipment.

For large low-voltage (LV) motors, such as 100 HP and above, there is no economical alternative other than DOL starting. One can, however, employ a delayed-action coupling or use starting categories in computer-based programs. Starting categories allow for starting the motor lightly and quickly and then simulate step or ramp change of loading.

9.2 Series impedance

A resistance or reactance can be used in series with motor winding during starting. Then, by using a contactor, the series impedance can be short-circuited. If a series reactance is used in the starting, the power factor will be poor and produce significant disturbance in the line. If a series resistance is used, then the power factor will be better, but the losses in the resistance will be high. Standard reactors are available to limit the starting voltages at the motor terminal to 50%, 75%, and 90% of the terminal voltage at the instant of starting. When starting with a series reactance, the kVA drawn from the supply is reduced directly proportional to the applied voltage and the motor torque is reduced proportional to the square of the voltage.

9.3 Shunt capacitor

A starting capacitor is switched with the motor, which compensates part of the reactive kvar drawn by the starting motor. The bank size is usually selected to provide about 50% of the motor-starting kvar. The capacitor is switched off at about 95% of the motor-rated speed, and the motor current drops to about full load. In case of large capacitors, the starting capacitor is switched on ¼ to ½ cycle before the motor is started. The salient features of this method are:

— The method improves the acceleration torque and reduces acceleration time, which makes it suitable for high-inertia or high-starting-torque loads.

A resonance check shall be made to ensure that the selected capacitor bank does not create a system problem. Shunt capacitors can cause overvoltages when interacting with the magnetic circuit of the induction motors. Therefore, the shunt capacitors have to be switched off as soon as the starting is completed. However, switching off the shunt capacitors requires further consideration from the transient recovery voltage point of view.

9.4 Reactor/choke

A reactor is connected in the motor circuit, either in the line or at the neutral end, during the start of the motor. The reactor is bypassed by switching a contactor or a circuit breaker when the motor has attained the rated speed. The starting current is reduced linearly, and the torque is reduced by approximately the square of the voltage at the motor terminals. One advantage of the reactor starting is that the motor torque increases with the speed as the starting power factor improves. This increase in torque is an added boost for synchronous motors, where the motor torque drops off at the end of the acceleration. The reactor ohmic value must be selected to reduce the motor-starting current drawn from the system to a value that will cause acceptable voltage flicker, and at the same time provide sufficient voltage at the motor terminals to accelerate the load.

9.5 Reactor–capacitor

This method is a combination of reactor and capacitor starting. This method can be used where the network is weak and reactive kvar is needed to improve motor performance during acceleration.

9.6 Partial winding

This method can be used for applications where a synchronous motor is started unloaded. The motor is wound with two sets of wye-connected stator windings, with the neutral end of one winding connected through a vacuum contactor or a circuit breaker. Upon starting, the contactor at the neutral end is open, and only one winding is in operation. The contactor is closed just after the motor has reached the synchronous speed, and the motor excitation is turned on. With this arrangement, the motor-starting (inrush) current is on the order of 65% to 75% of the normal starting current. This method offers a limited reduction in starting current, relatively low starting torque, and is not suitable for all ratings and speeds.

9.7 Wye/delta (Y-∆)

For small- and medium-size motors, the wye/delta starter can be used. The stator winding is connected in wye during the starting and in delta for the running. This starter is the simplest form of mechanical equipment and is suitable for small- and medium-size motors. In a wye–delta start, the starting torque is reduced to 30% of the normal starting torque.

Wye (Y)-start, delta (Δ)-run starting delivers 57.7% of normal starting line current with full voltage at the motor terminals. The starting current at any other voltage is, correspondingly, reduced by the same amount. Part winding starting allows 60% of normal starting line current at full voltage and reduces inrush accordingly at other voltages.

9.8 Captive transformer

The motor is energized through a two-winding transformer. The switching and protection are provided at the primary only. The transformer must be sized and built for motor-starting duty (impact loading). The salient features are:

- Can be used for large motors where the switching is done at a higher voltage than the motor-rated voltage, e.g., a 50 000 HP, 13.8 kV motor can be switched at 34.5 kV through a captive transformer.
- Reduces voltage flicker on the rest of the system.
- Reduces short-circuit currents from the motor to the primary switchgear and from the system to the motor.
- High-resistance grounding can be provided for the motor, thus reducing iron damage.

9.9 Autotransformer

This method is similar to the reactor start, except that an autotransformer is switched into the motor circuit during starting and bypassed at the end of the start. Two switching arrangements, open transition and closed transition, are used. Salient features include:

- Usually provided with 80%, 65%, and 50% taps. This permits the adjustment of the motor terminal voltage.
- Two additional contactors or circuit breakers and an autotransformer are required.
- The starting torque as seen in the network is reduced as the square of the transformer ratio.
- Because the motor current is greater than that in the line with an autotransformer starter, the starter produces more torque per ampere of line current.

If autotransformer reduced–voltage starting is used, motor inrush will be reduced by the appropriate factor from Table 4. If, for example, normal inrush is 6 times full-load current and an 80% tap autotransformer starter is applied, the actual inrush multiplier used for determining the appropriate motor representation in the calculation is (6) (0.64) = 3.84 × full-load current. Resistor or reactor starting limits the line starting current by the same amount as motor terminal voltage is reduced (i.e., 65% of applied bus voltage gives 65% of normal line starting current).

Table 4—Autotransformer line starting current

Autotransformer tap (% of line voltage)	Line starting current (% of normal at full voltage)
50	25
65	42
80	64

9.10 Electronic soft-starters

This method is known as a "soft start" and is basically a reduced-voltage starting method similar to a reactor start. In this method, a rectifier-inverter using an insulated gate bipolar transistor (IGBT) is applied to vary the voltage at the motor terminals to reduce the starting current. Because the frequency remains the same, the motor-starting torque is also reduced in proportion to the voltage squared. The soft-start controller is bypassed by switching a contactor or circuit breaker when the motor has attained the rated speed. Because the output waveform from the controller is not a sine wave, there is some reduction in the motor torque compared with the reactor start. The controller will also inject current harmonics into the power system during the starting period. This method is not suitable for high-inertia and high-torque loads.

9.11 Variable frequency drive/adjustable speed drive

Frequency static converters are capable of producing variable voltage and frequency, V_s, f_1. A coordination of V_s with f_1 is required. In this method, the ratio of voltage to frequency (volt/Hz) is maintained constant during the acceleration period or operating speed range. Such a coordination may be "driven" by an optimization criterion or by flux linkage control in the machine to secure fast torque response. The voltage and frequency of the power supply to the motor is reduced to a low value to increase the ratio of the motor torque to the motor-starting current. At reduced frequency, the applied voltage and starting current are lower. The motor is accelerated through a frequency converter, and upon reaching the system frequency, the motor is transferred to the network. The motor-starting torque can be shaped to suit the load characteristics. Two types of drives—load commuted inverter (LCI) and pulse-width modulation (PWM)—are used. LCI is a current source inverter and is common with synchronous motors. The PWM drive is a voltage-source inverter, using switching devices such as IGBT, integrated gate commutated thyristor (IGCT), or injection enhanced gate transistor (IEGT) to chop the dc into pulses. The salient features are:

- Smooth acceleration and a negligible voltage drop in the network
- No dynamic torques
- High cost and requires a large space
- One starter can be used for more than one motor
- Harmonic generation, with the order depending on the number of pulses; filters may be required

Various voltage-frequency relationships may be classified into four main categories:

- V/Hz scalar control
- Rotor flux vector control
- Stator flux vector control
- Direct torque and flux control

Historically, the V/Hz scalar control was first introduced and is used widely today for open loop speed control in driving fans, pumps, etc., which have the load torque dependent on speed squared, or more. The method is rather simple, but the torque response tends to be slow. For high torque response performance, separate flux and torque control much like in a dc machine is recommended. This is called *vector control*.

Figure 28 shows the V/Hz relationship and corresponding torque/speed curve.

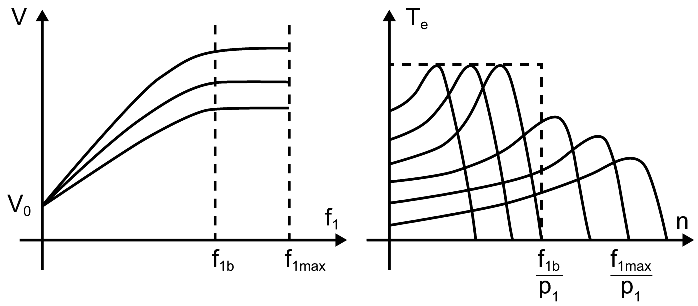


Figure 28 —V/Hz variation

Refer to IEEE Std 1566™-2015 for more information regarding VFD.

9.12 Voltage and frequency variation

Based on IEC 60034-1, motors are designed to operate successfully at rated load with a variation of:

— ±10% of rated voltage with rated frequency or
— ±5% of rated frequency with rated voltage or
— ±10% combined variation of voltage and frequency, provided that the frequency variation does not exceed +5%

Furthermore, IEC 60034-1 defines the impact of temperature rise caused by voltage and frequency fluctuations by using the following zones:

— Zone A: ±5% of rated voltage and ±2% of rated frequency
— Zone B: ±10% of rated voltage and +3/−5% of rated frequency

The torque developed by the motor at any speed is approximately proportional to the voltage squared and inversely proportional to the frequency squared. A voltage dip of 30% or higher for a few cycles could stall a fully-loaded motor. Figure 29 shows the effect of varying the voltage (where V_1 and V_2 are sample voltages) and Figure 30 shows the effect of varying the frequency (where f_1 and f_2 are sample frequencies) on the torque.

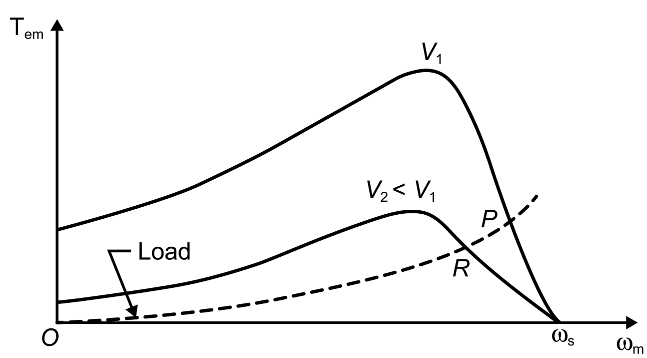


Figure 29 —Effect of voltage variation

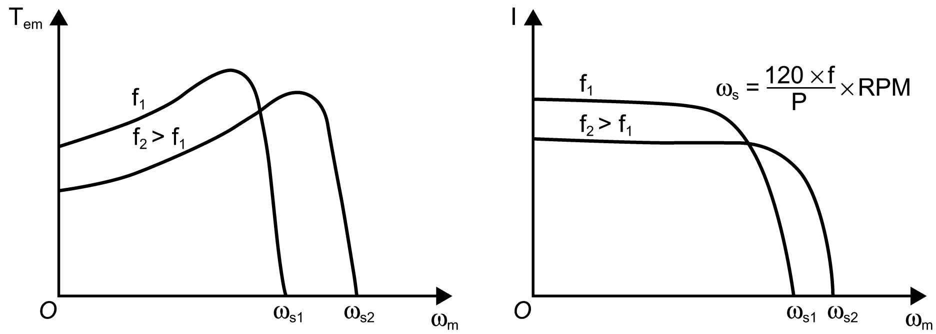


Figure 30 —Effect of frequency variation

For an unbalance in supply voltage, the motor current imbalance will be on the order of 6 to 10 times the voltage unbalance. The motor output must be reduced using the derating factors given in NEMA-MG1. Because the motor-protection relays are not calibrated for current unbalance of negative-sequence current, a proper setting based on voltage unbalance becomes a problem.

10. Required data

10.1 Overview

The electrical system is represented by suitable impedance values. Then the impedance values are converted to a common base.

10.2 Basic information

Since other loads on the system during motor starting affect the voltage available at the motor terminals, the information necessary for a load flow or short-circuit study is essentially the same as that required for a motor-starting study. This information is summarized below.

a) *Utility and generator impedances*. These values are extremely significant and should be as accurate as possible. Generally, they are obtained from local utility representatives and generator manufacturers. When representing the utility impedance, it should be based on the minimum capacity of the utility system in order to yield the most pessimistic results insofar as voltage drop problems are concerned. This is in direct opposition to the approach normally taken for a short-circuit analysis discussed in IEEE Std 3002.3™. Where exact generator data cannot be obtained, typical impedance values are available from the *Electrical Transmission and Distribution Reference Book* [B49] and Beeman [B3].

b) *Transmission lines*. Transmission lines are represented by positive- and zero-sequence impedances.

c) *Cables*. Cable impedances are presented by the positive- and zero-sequence impedance values. Additional parameters may be specified which include the number and size of conductors, conductor material, magnetic duct, or armor.

d) *Transformers*. Manufacturers' impedance information should be obtained where possible, especially for large units (i.e., 5000 kVA and larger). Standard impedances can usually be used with little error for smaller units (refer to 13.3 for tolerances to be applied to transformer impedances), and typical *X/R* ratios are available in IEEE Std C37.010™.

e) *Other components*. All system elements should be supplied with *R* and *X* values so an equivalent system impedance can be calculated.

f) *Load characteristics*. System loads should be detailed, including type (constant current, constant impedance, or constant kVA), power factor, and load factor, if any. Exact inrush (starting) characteristics should also be given for the motor to be started.

g) *Machine and load data*. Along with the aforementioned basic information, which is required for a voltage drop type of motor-starting analysis, several other items are also required for the detailed speed–torque and accelerating-time analysis. These include the WR^2 of the motor and load (with the WR^2 of the mechanical coupling or any gearing included) and speed–torque characteristics of both the motor and load.

For additional accuracy, speed versus current and speed versus power factor characteristics should be given for as exact a model as possible for the motor during starting. For some programs, constants for the motor-equivalent circuit given in Figure 31 can be either required input information or typical default values. This data must be obtained from the manufacturer since values are critical. Exciter/regulator data should also be obtained from the manufacturer for studies involving locally-connected generators.

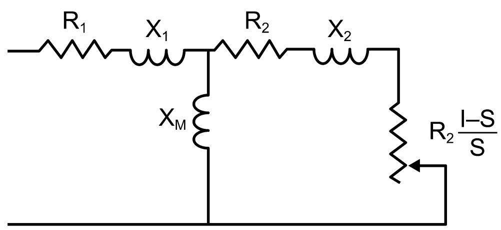


Figure 31 —Simplified equivalent circuit for a motor on starting

When special motor applications are involved, like high starting torque or low starting current, motor manufacturers may use special “deep bar” or double squirrel-cage motor rotor designs. These designs can be represented either by their torque/speed curves or by an equivalent electrical circuit model with two (or more) parallel rotor branches represented. This increases the complexity of the equivalent circuit and the corresponding mathematical solution beyond that of the more simplified single-rotor model depicted in Figure 31.

10.3 Motor starting

10.3.1 Bus data

Required bus data includes:

— Nominal kV, angle

— Load diversity factor

10.3.2 Branch data

Branch includes three-winding transformer, two-winding transformer, transmission line, cable, reactor, and impedance. Branch data also includes:

— Branch Z, R, X, or *X/R* values and units, tolerance, and temperatures, if applicable

- Cable and transmission line length and unit
- Transformer rated kV and kVA, tap and load tap-changing (LTC) settings
- Impedance base kV and base kVA

10.3.3 Power grid data

Required power grid data includes:

- Rated kV
- Minimum short-circuit megavolt ampere (MVA) (i.e., higher grid impedance and consequently more conservative to perform voltage drop study)
- Voltage at the point of interconnection (POI)

10.3.4 Static load data

Required static load data includes:

- Rated kV, kVA, and power factor
- Operating load

10.3.5 Motor-operated valve (MOV) data

Required motor-operated valve data includes:

- Rated kW/HP and kV
- Hammer blow and micro-switch flags
- Locked rotor (LR), no load (NL), normal, and rated torque (rated T)
- Current, PF, and time duration for each operation stage
- Operating load
- Voltage limits for start, seating/unseating, and travel time

10.3.6 Capacitor data

Required capacitor data includes:

- Rated kV
- Rated kvar/bank and number of banks
- Delta or wye connection

10.3.7 Lumped load data

Required lumped load data includes:

- Rated kV, kVA, and power factor
- Operating load

10.3.8 Variable frequency drive (VFD) data

Required VFD data includes:

- Bypass switch status
- Rated input/output kV, kVA, frequency, efficiency, and input power factor
- Operating input power factor, frequency, and V/Hz ratio
- Starting control type, control parameters, and current limit

10.3.9 Synchronous generator data

Required synchronous generator data includes:

- Operating mode (swing, voltage control, kvar control, or power factor control)
- Rated kV, kW, power factor, efficiency, poles
- X'_{di} and *X/R* ratio
- Operating generation data (voltage, kW, and kvar)

In addition to the above, the following parameters are required for full dynamic motor-acceleration studies:

- Direct axis and quadrature axis, subtransient and transient reactance, armature resistance, and open-circuit time constants for round rotor and salient pole
- Saturation factor and shaft damping factor
- Prime mover, coupling, and generator rated speed and moment of inertia
- Exciter, governor, and stabilizer model

10.3.10 Synchronous motor data

Required synchronous motor data includes:

- Rated HP or kW
- Rated kV
- Power factors and efficiencies at 110%, 100%, 75%, 50%, and 0% shaft loading
- Operating load

The parameters required for modeling starting motors and operating motors (large and small) in static and characteristic curve motor-starting studies are shown in Table 3. In addition to these, the parameters required for dynamic and full dynamic motor-acceleration studies include:

- Direct axis and quadrature axis, subtransient and transient reactance, armature resistance and open-circuit time constants for round rotor and salient pole
- Saturation factor and shaft damping factor
- Prime mover and coupling rated speed and moment of inertia
- Exciter model
- Mechanical load characteristics as function of speed

- Field current application time
- Field winding discharge resistance
- Motor, load, and coupling inertias
- Circuit model parameters (for starting motors only)

10.3.11 Induction motor data

Required induction motor data includes:

- Rated kW/HP and kV
- Power factors and efficiencies at 110%, 100%, 75%, 50%, and 0% shaft loading
- Operating load

The parameters required for modeling starting motors and operating motors (large and small) in static, characteristic curve, and dynamic motor-starting methods are shown in Table 3. In addition to the above parameters, required parameters for the full dynamic motor-acceleration studies include:

- Motor, load, and coupling inertias
- Mechanical load characteristics as function of speed

11. Data collection and preparation

11.1 Overview

The data required for performing motor-starting calculations may be obtained from different methods, depending on the type and stage of the study. If the study is for an existing system, the equipment parameters should be coming from equipment nameplate, manufacturer data sheet, design document, or field testing results, to the greatest extent possible. If the study is for the conceptual design of a system, generally typical data will be used. As the design progresses and manufacturer data or test data becomes available, it can be used to replace the typical data to continue with the calculation.

11.2 Equipment data from existing system

All parameters required for various types of equipment, especially starting motors, should be (as much as possible) obtained from nameplate of equipment, manufacturer-supplied data sheet, and testing results of the actual equipment. Although sometimes the nameplate and manufacturer-provided data sheet may be only for a class of equipment and is not guaranteed 100% accurate, they are still more accurate than typical data provided by some computer software or standards.

Typical data or library data provided by computer software may also be used for studies of an existing system. This is normally the case for a system that has been around for decades, when it is difficult to locate the manufacturer-provided data sheet. Additionally, it can be time consuming or not feasible to obtain all equipment data based on nameplate or manufacture data sheet, especially for less important equipment such as small motor or static load. In these cases, typical data can also be used.

11.3 Equipment data from new systems

For recently-built systems, it should be relatively easy to obtain nameplate, manufacturer data sheet, or system design document. It includes:

- Generation unit
- Synchronous motor
- Induction motor
- Switchgear, motor control center (MCC), switchboard, and panel board
- Transformer
- Transmission line and cable
- Current limiting reactor
- On-line capacitors
- Motor starters

11.4 Equipment test data

A test data sheet provides the most accurate representation of equipment. It should be used whenever it is available. Due to the additional cost involved, factory tests are conducted only on motors with large ratings, or if they are critical to the process. Sometimes equipment manufacturers may also provide testing data if such tests are requested at time of purchasing. The types of equipment that may have test data include:

- Transformer
- Generator
- Large synchronous or induction motor
- Capacitor, when available

11.5 Field measurement

Some field measurement data may also be needed for motor-starting calculation, as the operating condition can affect motor-starting results. These operating parameters include:

- Bus operating voltage value, including maximum voltage, minimum voltage, and normal operating voltage.
- System loading conditions, including maximum loading and minimum loading conditions. Note that a highly-loaded system condition generally indicates that more motors are operating.

11.6 Utility short-circuit contribution

Utility (power grid) is the most important current-contributing source to motor starting, especially at the medium-voltage level. Therefore, it is very important to obtain accurate parameters for the utility. The utility parameters can only be obtained from the utility company that has interface with the local system or from the transmission authority, where necessary.

Due to variation in utility operating conditions, it is normally preferred to obtain utility (i.e., at the grid or switchyard connection) short-circuit parameters for maximum and minimum contributions for both three-phase and single-phase fault. However, the purposes of a motor-starting study can usually be met by utilizing only the minimum three-phase short-circuit level (i.e., higher grid impedance and consequently more conservative to perform voltage drop/motor-starting study).

11.7 Motor nameplate

A critical part of making motors interchangeable is ensuring that nameplate information is common among manufacturers. The common language of the motor nameplate enables installation and maintenance personnel to quickly understand and recognize exactly what type of motor they are dealing with during a new installation or replacement procedure. As a basic requirement of the National Electrical Code (NEC), the motor nameplate must show the following information:

- Rated voltage or voltages
- Rated full-load amps for each voltage level
- Frequency
- Phase
- Rated full-load speed
- Insulation class and rated ambient temperature
- Rated horsepower
- Time rating
- Locked-rotor code letter
- Manufacturer's name and address

Additional information will normally appear on most nameplates as well (see Figure 32). This information might include the motor service factor, enclosure type, frame size, connection diagrams, and unique or special features (refer NEMA MG 1 [B37]). The best way to approach a basic understanding of what standardization means and to cover some of the material fundamental to standard induction motors is to examine in detail the nameplate information contained on a typical motor.

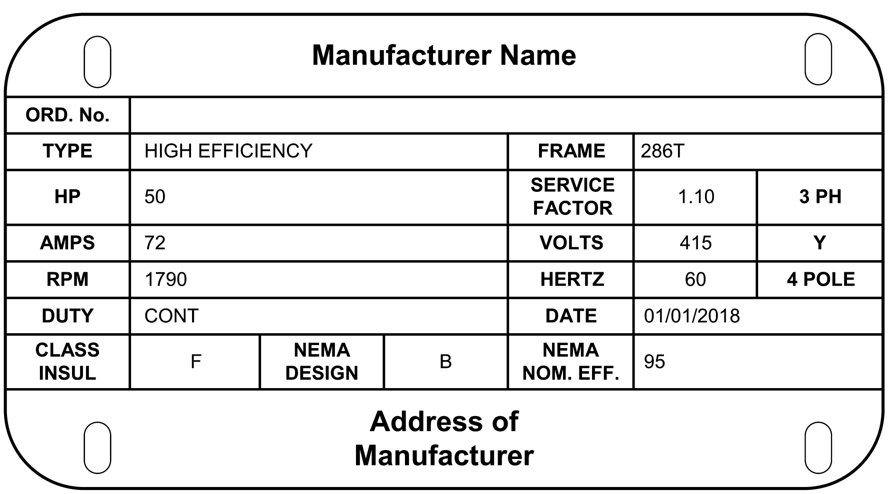


Figure 32 —Sample motor nameplate

11.8 Typical data

Table 5 shows a set of typical data from various sources that may be utilized in the event that the manufacturer's nameplate and data sheet fail to provide the required information (see Khan [B29]).

Table 5—Typical motor-starting power factor

Motor rating		Starting power factor
HP	kW	
≤ 50	≤ 37	0.40
100	75	0.30
500	375	0.20
1000	750	0.15
2500 to 7000	1875 to 5250	0.13
> 7000	> 5250	0.10

12. Model and data validation

12.1 Overview

Model and data validation is the most important task to be carried out before any system calculations can be conducted. The accuracy of simulation results from any software cannot be better than the accuracy of its input data and the models used to represent system equipment. From this point of view, the significance of model and data validation can never be overstressed.

12.2 Parameters and model to be validated

All the parameters affecting the accuracy of the calculation results should be validated, from short-circuit contributing elements, power transmission components, to pre-fault system-operating conditions.

- Power transmission equipment: Includes transformers, transmission lines, cables, reactors, and equivalent impedance components. Equipment parameter tolerance values should also be validated, such as transformer impedance tolerance and length tolerance of lines and cables. These tolerance values are used to account for uncertainty in equipment parameters.
- Pre-fault operating parameters: System configurations and operating voltage values.
- Short-circuit contributing sources: Include power utility and synchronous generators. The rating parameters and sequence impedance values of these components must be closely checked and validated.
- Motor models for static motor starting: Motor nameplate, starting torque, PF, and locked-rotor current.
- Motor models for dynamic analysis: Machine torque slip curve, connected load torque curve, and complete shaft inertia. Motor parameter estimation can be applied in certain computer software to obtain a motor characteristic curve or circuit model, if motor data is not available from the manufacturer.

In general, motor-starting calculations in a quality computer software should follow multiple methodologies to suit the study requirements.

12.3 Data and model validation

There are several methods that can be used to validate models and data:

— Check against data source, including nameplate and manufacturer data sheet. Data entry errors can often occur, especially for a larger system. Having a second, or even a third eye to validate data entry can save time for the whole project.

— Validate based on engineering common sense or rule of thumb. After data entry has been completed, run several quick motor-starting calculations and check the results based on engineering common sense. It can help to spot modeling mistakes. For example, if the motor-starting time is not equal to the motor-starting time specified in the motor data sheet, then there has been a data entry error in the computer program.

13. Study scenarios

13.1 Overview

From system design, maintenance, and operation point view, different study scenarios need to be considered. Most-extreme cases, such as maximum and minimum voltage support from sources, need to be considered.

13.2 Types of motor-starting simulation

13.2.1 Single motor start (static)

During the acceleration period, the motor is represented by its locked-rotor impedance, which draws the maximum possible current from the system and has the most severe effect on other loads in the system. Once the acceleration period has passed, the starting motor is changed to a constant kVA load and software simulates the load-ramping process according to the starting and final loads (if specified).

Applications

— Used for systems with strong and weak power grid support, with or without generators

— When dynamic motor information is missing

— Typically used to analyze impact of critical LV or large medium-voltage (MV) motors

— Can assess sequential and/or concurrent start of multiple motors

— Existing system where motor is known to start without problem, hence starting time determination is not a requirement

— Determining adequate tap position

Advantages

— Generator dynamics can be ignored due to the presence of a strong power source, such as a power grid with high MVAsc

— This study can be conducted even when dynamic model information, such as motor torque slip characteristics, inertia, and load torque characteristics, are not available

Disadvantages

— Since a dynamic model is not utilized, it is not possible to determine starting time of motors.

— Generator dynamics are not considered, hence it is a conservative approach. Credit for generator exciter cannot be considered.

Figure 33 shows the motor-starting results (one-line diagram and time series plots) for a single motor-starting study using a static model, fixed LRC and starting time. Figure 34 shows the generator response for the same study. Abbreviations are defined in 14.3.

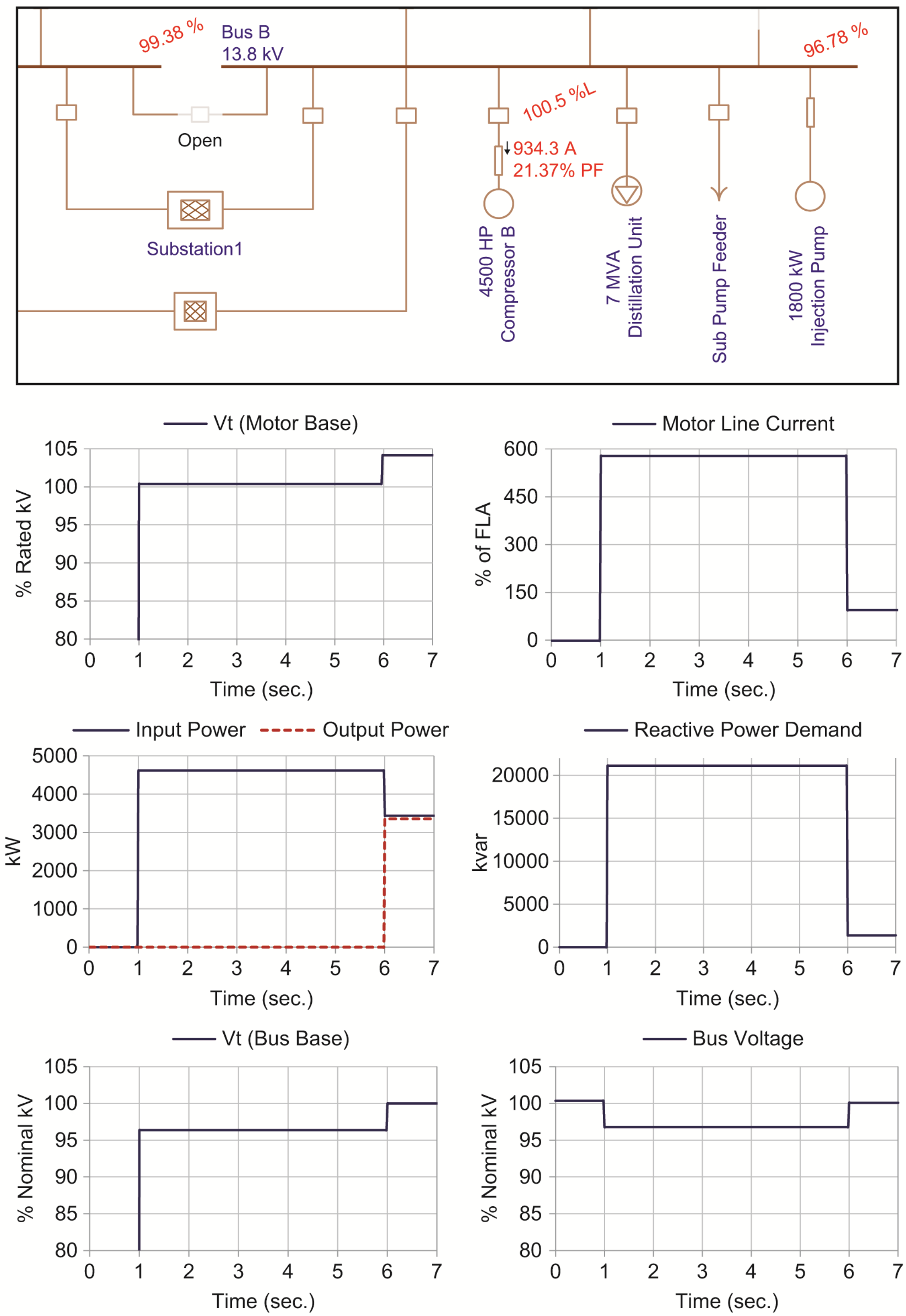


Figure 33—Static motor starting, motor response

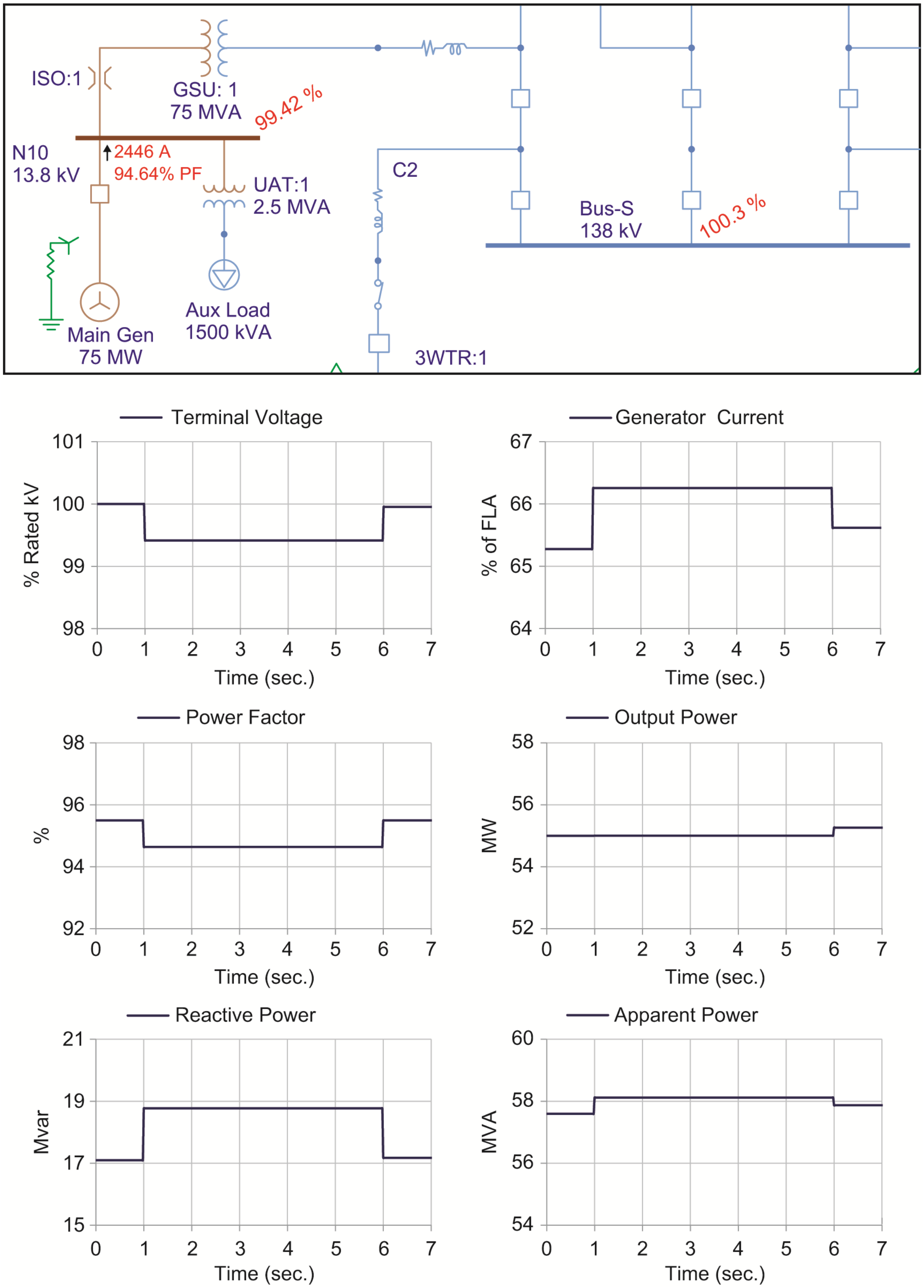


Figure 34 —Static motor starting, generator response

13.2.2 Single motor start (dynamic)

Applications

- Use for systems with weak power grid support when compared with the required starting kVA of the motor and/or islanded system configurations
- Dynamic motor information is available or can be estimated
- Typically used to analyze impact as well as determine acceleration time of critical LV or large MV motor
- Sequential and/or concurrent start of multiple motors
- Used in existing systems where motor is known to have problems starting or the starting device is being added/modified; Also used for new systems in order to determine motor protection settings
- Used to determine appropriate tap position

Advantages

- Including system dynamics (generator, motor, and load) will provide a more accurate assessment of the prospective parameters (including voltages, speed, current, torque, and others) during motor starting

Disadvantages

- Requires motor and driven load dynamic model information, which may not always be available. Therefore, the analysis is limited to typically critical LV motors and large MV motors only.
- Generator dynamics are required, hence it is a realistic approach, but requires generator controls such as exciter and governor controls to be specified as well. This information may not be readily available especially for older facilities. This type of analysis also requires the generator model to be tuned against field measurements for optimum accuracy, which contributes to a higher cost.

Figure 35 shows the motor-starting results (one-line diagram and time series plots) for a single motor-starting study using a dynamic model. Figure 36 shows the generator response for the same study. Abbreviations are defined in 13.3.

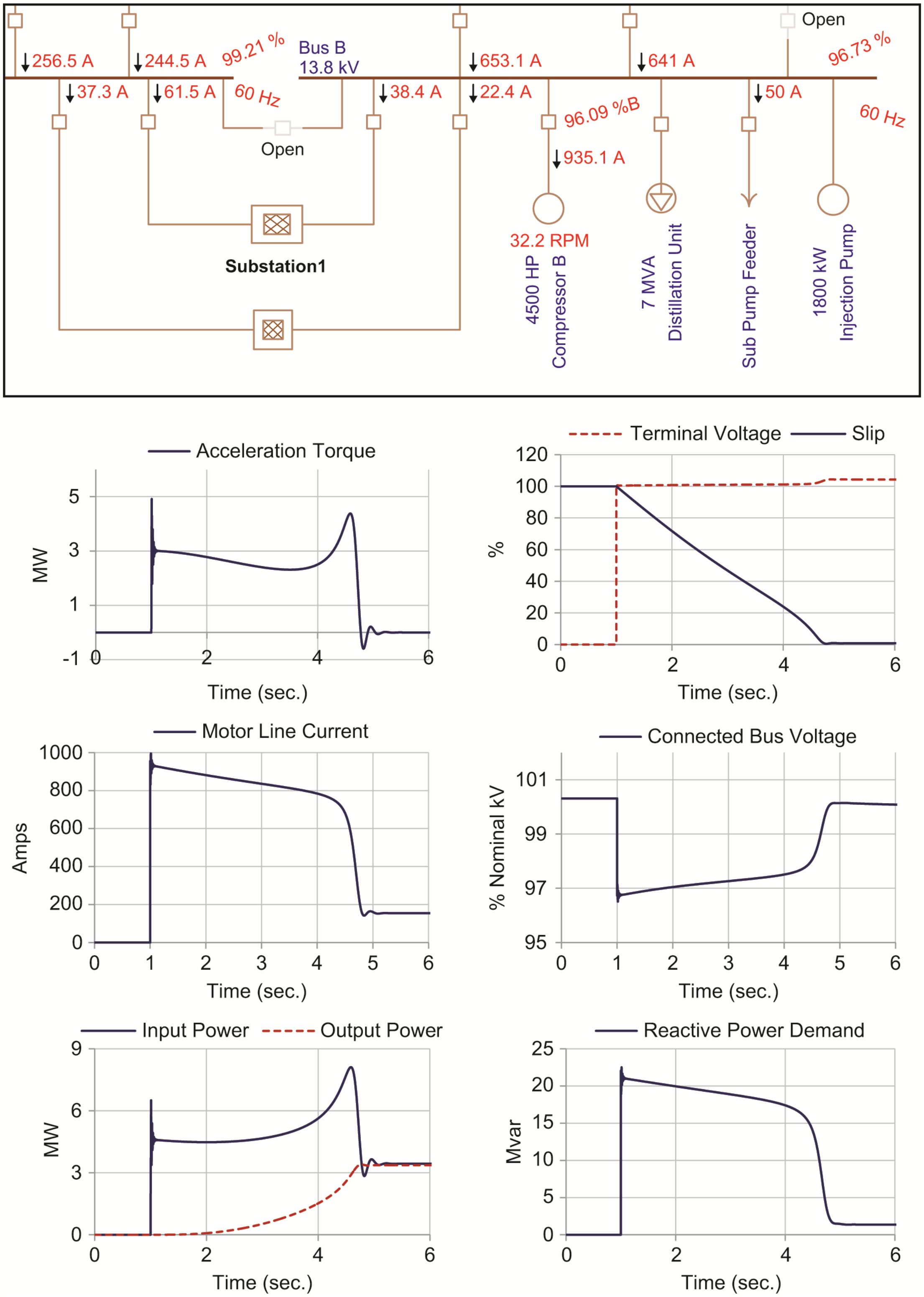


Figure 35 —Dynamic motor starting, motor response

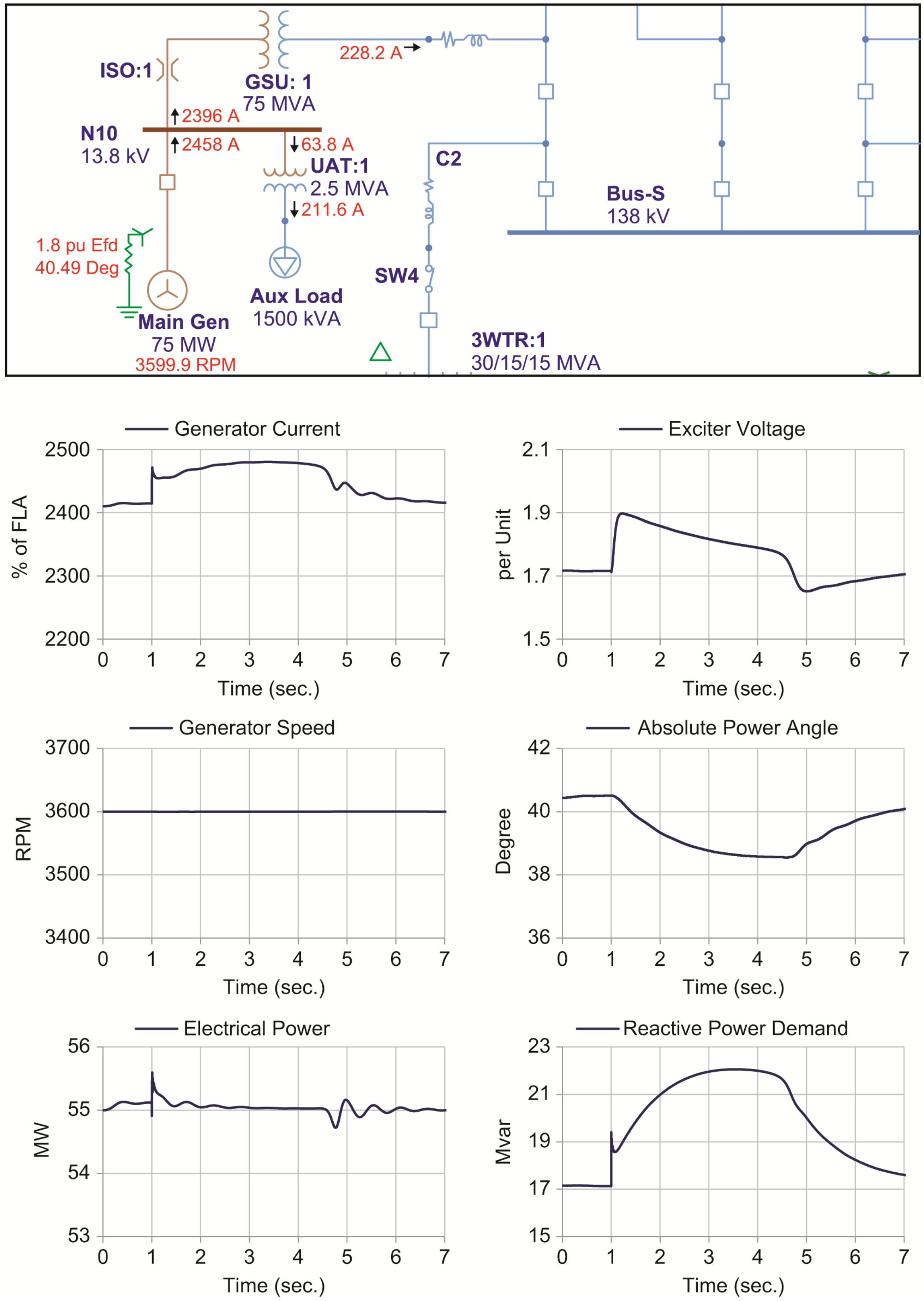


Figure 36 —Dynamic motor starting, generator response

13.2.3 Sequential motor starting

This type of simulation is used to determine the effect of sequential motor starts with or without other system events that may impact the motor-acceleration calculation. Typically, the sequence of starts may be defined in the study parameters based on expected operating scenarios for the system. Sequence of starts may be one motor at a time, or groups of motors starting sequentially in various orders and combinations.

Figure 37 shows a sequence of events where the motors are started in sequence and a capacitor bank is switched off with the utility voltages at nominal levels under initial conditions based on the scenario shown in Table 6.

Table 6—Motor-starting events

Time	Event
t = 1 s	Compressor B start with 100% load
t = 2 s	Compressor C start with 100% load
	CAP1 0.3 Mvar, switched off
Category	**Name and value**
Loading	Design, 100%
Generation	Design, 100%

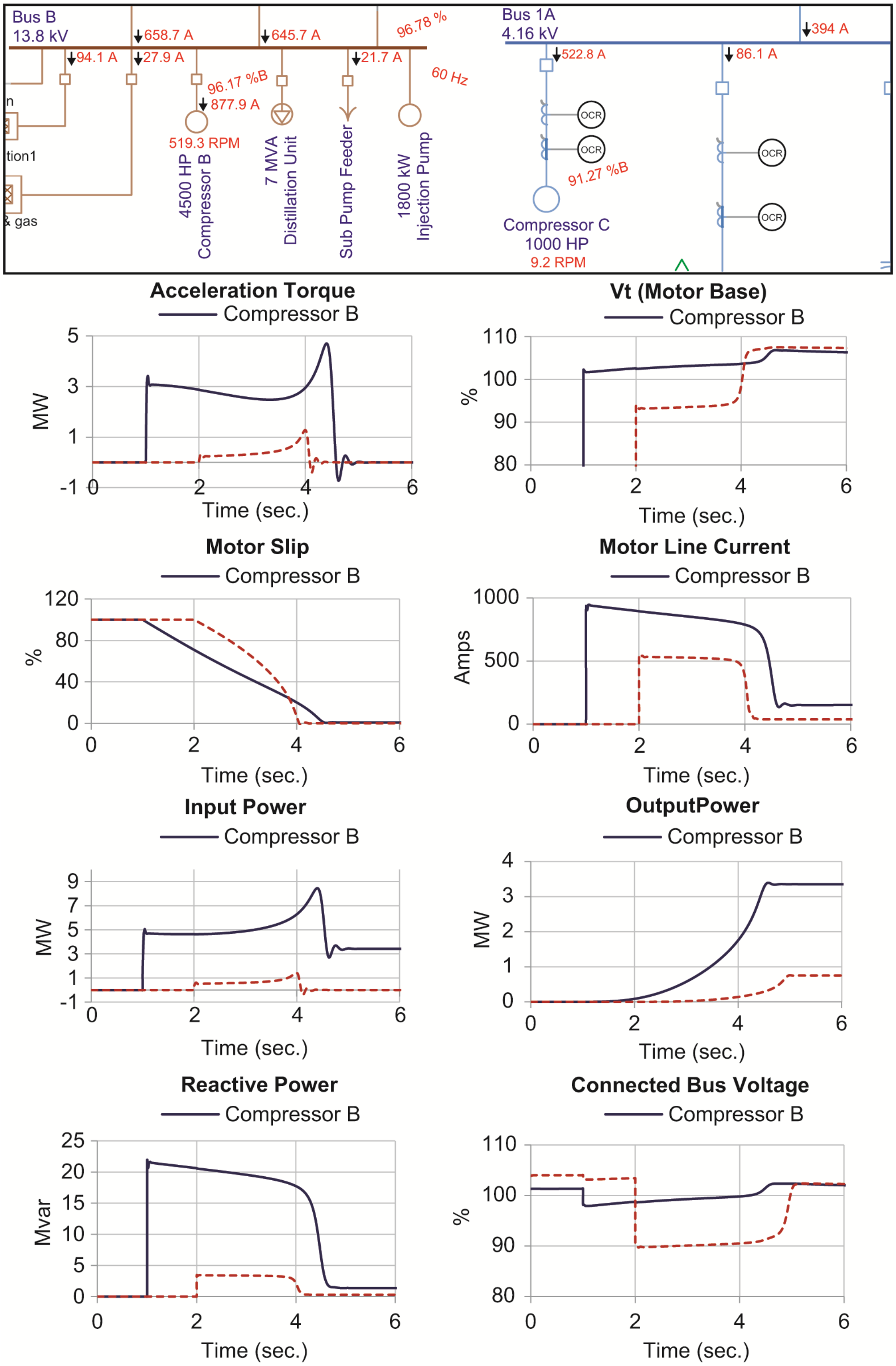


Figure 37 —Sequential dynamic motor starting

13.2.4 Simultaneous motor starting

If the process requires multiple motors to start on the same bus or on various buses, then the computer program can be set up to start motors by specifying them individually or in groups. However, the nature of the process being served can impose rigorous challenges in terms of motor starting. Some systems require that a number of motors be started simultaneously, other applications may present the situation where a great many motors will attempt to restart simultaneously following a system disturbance. When performing a motor-starting study, it is important that all normal and abnormal process operating conditions are reflected in the array of cases defined for simulation.

Figure 38 shows the motor terminal voltage of two simultaneously started motors along with its time series plots for the torque, voltage, current, slip, and power.

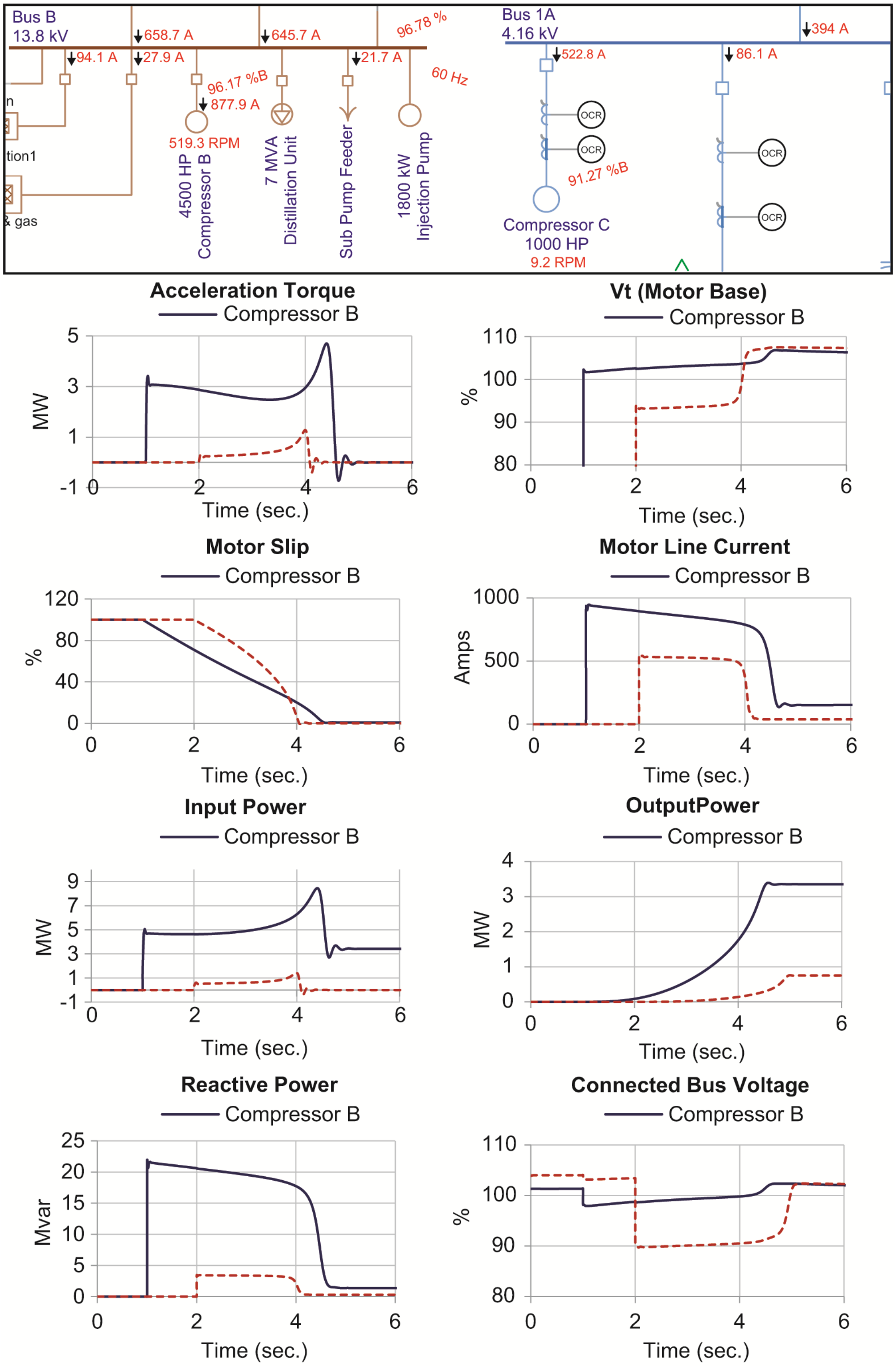


Figure 38 —Simultaneous dynamic motor starting

13.2.5 Motor starting using VFD

The variable frequency drive (VFD), also called adjustable speed drive (ASD) or adjustable frequency drive (AFD) in some applications, includes models for motor-starting control schemes, rectifier/inverter/dc-link dynamics, and harmonic spectrum. It can be used to simulate VFD behavior in normal speed-control operation, during motor acceleration, and under disturbances to study its impact on system dynamics.

Computer software provides flexible representation and modeling for VFD systems as shown in Figure 39. It can be inserted between a motor and its terminal bus or connected to a motor through transformers and cables to simulate a long distance power system. In some software, on the input side of VFD, it can be connected to multiple transformers directly to represent 12-, 18-, or 24-pulse VFDs.

Computer software has multiple operating categories allowing the user to specify different output frequency values and corresponding output voltage according to user-specified V/Hz ratio. VFD load is calculated based on VFD output frequency and load frequency characteristics. Multiple options for VFD input power factor are provided: VFD rated power factor, VFD output load power factor, and user-specified power factor.

Multiple control types may be provided to simulate VFD operations during motor starting for all available control schemes in today's applications. The frequency control scheme allows the user to freely specify VFD output frequency and Volt/Hz as functions of time. This control type can be easily used to model constant power control, constant torque control, and any other forms of controls. The torque control scheme allows the user to specify motor torque as function of time with a maximum current limit. A voltage boost effect is also simulated in the motor-starting simulation. Note that when VFD is only used as a soft starter, then its kVA rating is reduced to about 30% of motor rating. Figure 40 shows the impact of varying frequency on the torque/speed curve.

The rectifier/inverter/dc-link and dynamic control modeling allows the user to simulate the impact of VFD operations on a power system under disturbances, such as sudden load variations, VFD frequency change, or faults in the system.

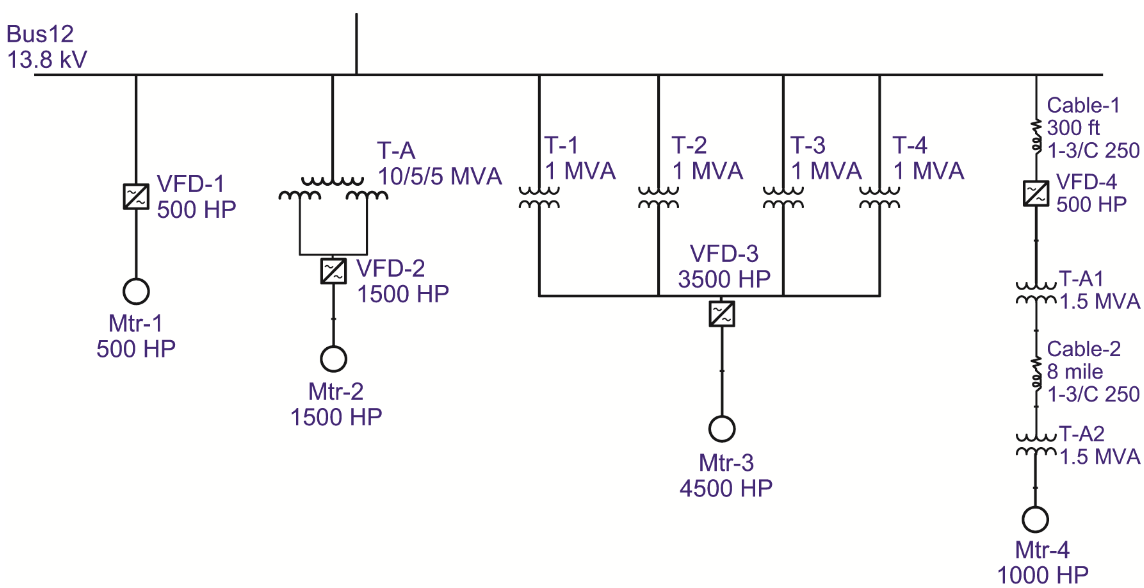


Figure 39 —Typical VFD connections

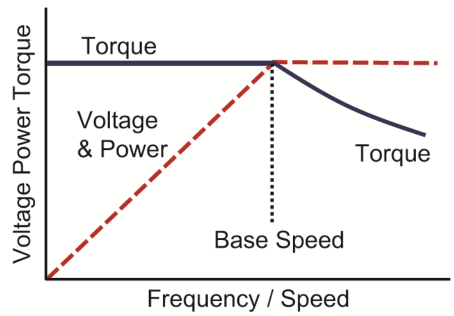


Figure 40 —V/Hz impact on torque/speed curve

13.3 Tolerances and adjustments

Tolerances are applied for new designs where the equipment specifications, such as cable lengths and transformer impedances, are either unknown or are in the process of being specified for manufacturing. Vendors typically supply, or custom build, equipment with some manufacturing tolerances (e.g., transformer impedance tolerances for new transformers may be ±7.5% for transformers less than 7500 kVA). These tolerances may be considered in the computer software, such as tolerance adjustments to length, equipment resistance, and impedance. Once the actual/component specific test results have been provided by the manufacturer, then impedance tolerances can be removed. Cable or overhead line tolerances may be removed once the actual pull length is known. In some software, tolerance adjustment can be applied based on the individual equipment percent tolerance setting or based on a globally value. Motor-starting calculations typically increase the cable length by the specified percent tolerance resulting in larger impedance and consequently a larger voltage drop; hence more conservative results. For example, if the length of the cable is 60.96 m (200 ft) and the tolerance is 5%, then the adjusted cable length used in the dynamic analysis calculation is 64.008 m (210 ft).

13.4 Starting load of accelerating motors

In the motor-acceleration calculations, the difference between the motor torque and the load torque is the motor-acceleration torque. Load-torque models may be specified as torque in percent as a function of normalized motor speed or as a percent of rated values. Note that manufacturers provide motor load torque based on motor-rated mechanical output. A typical motor load curve is shown in Figure 41.

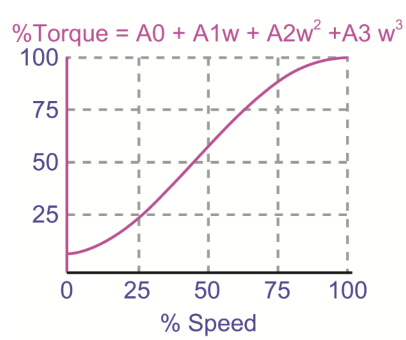


Figure 41—Typical motor load curve

13.5 Post-start load change

It may be possible that a motor with 100% load may not be able to start with the acceptable voltage drop or may take longer than tolerable to start. In such a case, it may be necessary to start the motor with less than 100% load connected to the motor shaft. Typical examples include starting a high-pressure centrifugal pump with the inlet valve slightly open and the discharge valve closed.

In this case, the motor does not experience significant load on the drive shaft when starting up since the impeller is spinning with only the fluid in the pump chamber. After the motor has come up to full-speed, the inlet and the discharge valves are opened allowing the fluid to flow through the pump thereby increasing the fluid load on the impeller. Note that incorrect timing on such a process can result in cavitation and damage the equipment. As can be seen from Figure 42, the load torque demand on the motor is lower with the discharge valve closed versus open at the time the motor is started.

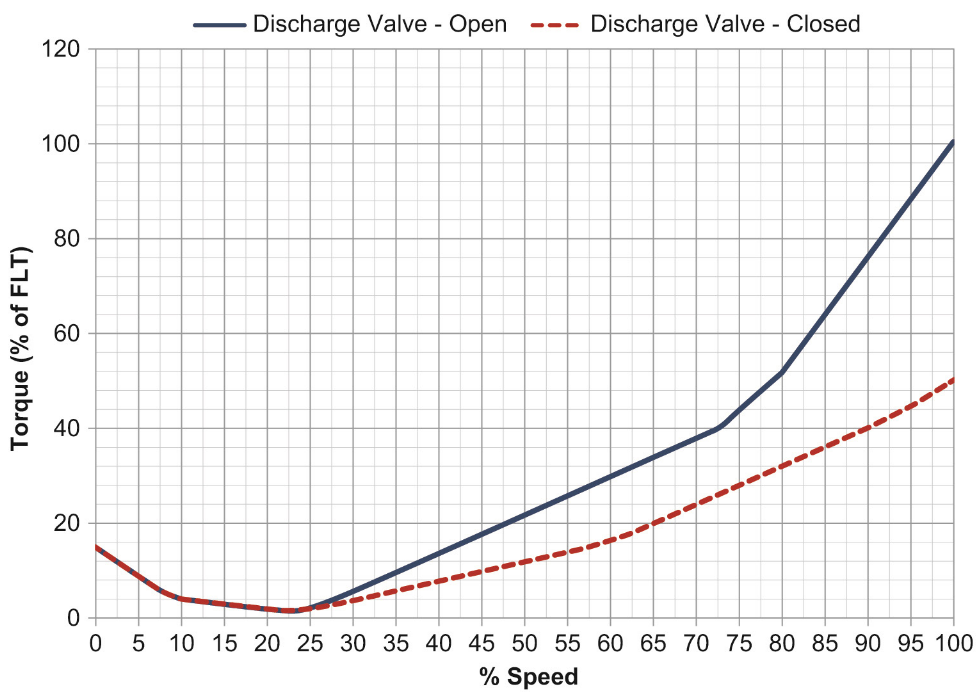


Figure 42—Centrifugal pump load curves under various conditions

A similar case can be analyzed with starting a large fan with the exhaust vanes closed and then opening them after the fan has come up to full speed. In order to simulate these conditions in a computer program, an option for load change may be utilized. The load change simulation allows the motor to start with a user-defined initial load (< 100%) and then, after reaching steady-state, the computer program can automatically ramp or create step change in load to another loading level, typically to 100%, as shown in Figure 43.

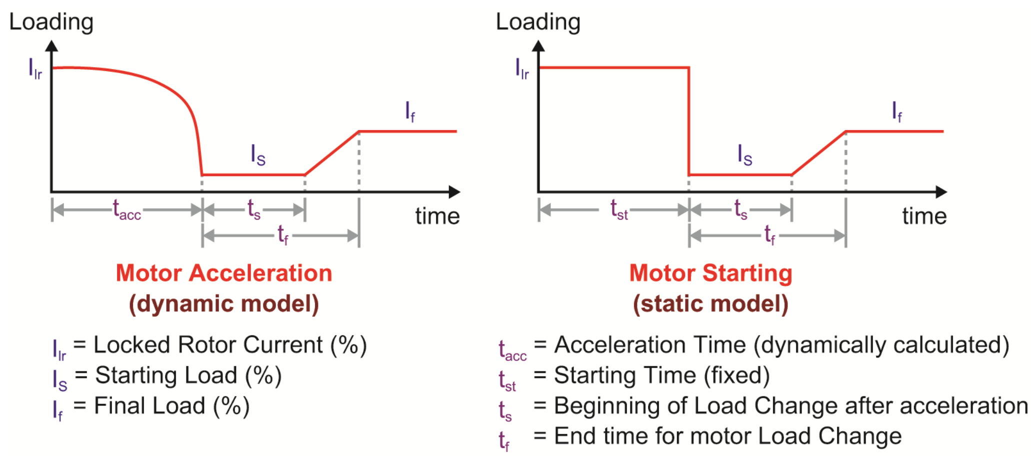


Figure 43—Load change simulation

13.6 Load transition by bus transfer

If a bus transfer has to be simulated during a motor-starting simulation, then such a load transfer may be defined in two methods. One option is to explicitly define the circuit breaker time that will be used to initiate a make-before-break or break-before-make type of transfer. This method should be used when solving the complete system dynamics and there are large dynamically-modeled loads being transferred. The second option is to use load transition, whereby reduction of load on one bus is simulated in parallel with reduction in load on another bus mimicking load transfer. The second option should only be used for non-dynamically relatively smaller loads on a bus, or a case where complete system dynamics is not being utilized.

14. Results and reports

14.1 Overview

After running the study, reports should be created in the format preferred by the client who commissioned the study.

14.2 Motor-starting study results and report format

14.2.1 Overview

The minimum required results and additional results to facilitate understanding of simulation include the following report sections.

14.2.2 System input data

System input data is used in the motor-starting study, including bus input data with the operating load connected to each bus, system branch data, branch connection summary, and generator and utility machine data. A sample input data tabulation is shown in Figure 44.

Synchronous Machine Parameters

Machine			Rating		Positive Sequence Impedance(%)								Zero Seq.Z(%)		
ID	Type	Model	MVA	IV	Ra	Xd"	Xd'	Xd	Xq"	Xq'	Xq	X1	X/R	R0	X0
Utility	Power Grid	N/A	1200.000	34.500	2.22		99.98							1.32	59.50
Gen2	Generator	Subtransient, Round-Rotor	11.765	13.800	0.25	12.00	23.00	110.00	12.00	15.00	108.00	11.00	48.00	0.25	12.00
Gen3	Generator	Subtransient, Round-Rotor	3.529	4.160	0.25	12.00	23.00	110.00	12.00	15.00	108.00	11.00	48.00	0.25	12.00
Gen1	Generator	Subtransient, Round-Rotor	8.824	13.800	0.25	12.00	23.00	110.00	12.00	15.00	108.00	11.00	48.00	0.25	12.00
Syn1	Motor	Subtransient, Round-Rotor	1.170	13.200	0.56	15.38	23.00	110.00	12.00	15.00	108.00	11.00			

Machine	Connected Bus	Time Constants (Sec.)				H(Sec.), D(MWpu/Hz) & Saturation					Generator or Loading		Grounding		
ID	ID	Ido"	Ido'	Iqo"	Iqo'	H	%D	8100	8120	Sbmal	MW	Mvar	Conn.	Type	Amp
Gen2	Bus10	0.002	5.600	0.002	3.700	0.5	5.00	1.070	1.180	0.800	0.000	0.000	Wye	Open	
Gen3	Bus12	0.002	5.600	0.002	3.700	1	5.00	1.070	1.180	0.800	3.529	0.000	Wye	Open	
Gen1	Sub2B	0.002	5.600	0.002	3.700	0.9	5.00	1.070	1.180	0.800	6.300	0.000	Wye	Solid	
Syn1	Sub2B	0.002	5.600	0.002	3.700	0.799	2.00	1.070	1.180		0.995	-0.617	Wye	Open	

Machine		Generator/Motor			Coupling			Prime Mover/Load			Equivalent Total		
ID	Type	RPM	WR^C	H	RPM	WR^C	H	RPM	WR^C	H	RPM	WR^C	H
Gen2	Gen.	1800	0	0	1800	0	0	1800	7860	0.5	1800	7860	0.5
Gen3	Gen.	1800	0	0	1800	0	0	1800	4715	1	1800	4715	1
Gen1	Gen.	1800	10610	0.9	1800	0	0	1800	0	0	1800	10610	0.9
Syn1	Syn. Mtr	1800	610	0.39	1800	40	0.026	1800	600	0.384	1800	1250	0.799

WR^C: lb-ff H: MW-Sec/MVA

Machine	Nameplate						Load Torque (= A0 + A1 ω + A2 ω^2 + A3 ω^3)				
ID	Quantity	HP/OW	RPM	FLA	%PF	%Eff	Model ID	A0	A1	A2	A3
Syn1	1	1250.00	1800	51.19	-85.00	93.70	COMP CENT	10.0	-91.0	321.0	-147.0

Figure 44—Synchronous machine input data

14.2.3 Switching motor and static load data

The switching motor and static load data printed include the motor nameplate data, equivalent cable data, and the switching static load data. For dynamic acceleration studies, the motor dynamic model and load model data are also printed in this section.

14.2.4 Switching event data

This section of the output tabulation lists, in the sequence of time events, every load-switching action, generation category change, and bus-loading change from load transitions. It is intended to provide a summary of all the actions that are to be simulated in the study. A sample of induction motor starting at time equal to 0.2 s is shown in Figure 45.

Sequence of Events

Time Event		Switching Load				% Loading		Load Change Time		Motor Load		Static Load	
Name	Time	ID	Type	Action	Category	Start	Final	Begin	End	MW	Mvar	MW	Mvar
1	0.200	M1	Ind. Motor	Start	Normal	100.0	100.0	0.00	0.00				

Figure 45—Sequence of events report

14.2.5 Event load flow tabulation

For each specified time event, whether there are switching actions or not, the module will run a load flow calculation and report the result in this section. This feature provides you with a way to inspect system-operating conditions at any time during motor-starting simulation. The module also runs a load flow at the end of the total simulation time and prints the results in this section.

14.2.6 Tabulated simulation results

This section tabulates the simulation results for each switching motor as functions of time at the specified plot time step. The tabulated results include motor slip, motor terminal voltage, bus voltage, motor current, and motor real power input. A sample of induction motor starting at time equal to 0.2 s is shown in Figure 46.

Motor Acceleration

Induction Motor ID: M1

Time	Slip	Current	% Terminal Voltage		% Bus	Torque (% FLT)		Time	Slip	Current	% Terminal Voltage		% Bus	Torque (% FLT)	
(Sec.)	(%)	(% FLA)	KVb Load	KVb Bus	Voltage	Motor	Load	(Sec.)	(%)	(% FLA)	KVb Load	KVb Bus	Voltage	Motor	Load
0.000	100.00	0.00	0.00	0.00	98.22	0.00	0.00	**0.020**	100.00	0.00	0.00	0.00	98.22	0.00	0.00
0.040	100.00	0.00	0.00	0.00	98.22	0.00	0.00	**0.060**	100.00	0.00	0.00	0.00	98.22	0.00	0.00
0.080	100.00	0.00	0.00	0.00	98.22	0.00	0.00	**0.100**	100.00	0.00	0.00	0.00	98.22	0.00	0.00
0.120	100.00	0.00	0.00	0.00	98.22	0.00	0.00	**0.140**	100.00	0.00	0.00	0.00	98.22	0.00	0.00
0.160	100.00	0.00	0.00	0.00	98.22	0.00	0.00	**0.180**	100.00	0.00	0.00	0.00	98.22	0.00	0.00
0.200	100.00	451.30	99.51	95.69	95.69	34.92	10.00	**0.220**	99.64	451.21	99.52	95.69	95.69	35.03	9.67
0.240	99.27	451.12	99.52	95.69	95.69	35.15	9.35	**0.260**	98.89	451.02	99.52	95.69	95.69	35.27	9.03
0.280	98.51	450.93	99.52	95.69	95.69	35.39	8.72	**0.300**	98.12	450.83	99.52	95.69	95.69	35.51	8.40
0.320	97.73	450.73	99.52	95.69	95.69	35.64	8.10	**0.340**	97.33	450.63	99.52	95.69	95.69	35.77	7.80
0.360	96.92	450.53	99.52	95.69	95.69	35.90	7.50	**0.380**	96.51	450.43	99.52	95.69	95.69	36.04	7.21
0.400	96.09	450.32	99.52	95.69	95.69	36.18	6.92	**0.420**	95.66	450.22	99.52	95.69	95.69	36.32	6.65

Figure 46—Motor-acceleration tabulation

14.2.7 Motor-starting alerts

In some software, the user can specify the limits to raise critical and marginal alerts for a motor-starting simulation. These limits should be allowed to be set globally and/or at individual motor/bus levels. The alerts should consist of three categories: alerts on starting motors, alerts on generator operating conditions, and alerts on bus voltage. Each category should also consist of several sub-types. A sample is shown in Figure 47.

- Starting motor and motor-operated valve (MOV) alert
  - Terminal voltage
  - Start time limit
  - Slip (fail to start)
- Bus voltage
  - Starting motor bus
  - Generator/grid bus

  - Voltage ranges (>, <, < >)
- Generator
  - Rating
  - Engine rating
  - Engine peak rating
  - Exciter peak rating

%Alert Settings

	Critical	Marginal	
Starting Motors/MOV			
MOV Terminal Voltage	≤ 80.00	90.00 (Vmtr, rate)	
Motor Terminal Voltage	< 80.00	90.00 (Vmtr, rate)	
Failed to Start, Slip Kept	≥ 5.00		
Generator/Engine/Exciter Rating			**Min. Span (sec.)**
Generator Rating	100.00	95.00	0.00
Engine Continuous Rating	100.00	95.00	0.00
Engine Peak Rating	100.00	95.00	0.00
Exciter Peak Rating	100.00	95.00	0.00
Bus Voltage Group			**Min. Dip Width (Sec.)**
Starting Motor Bus	VBus ≤ 80.00	90.00	0.00
Grid/Generator Bus	VBus ≤ 92.00	95.00	0.00
HV Bus, kV ≥ 10.00	VBus ≤ 90.00	95.00	0.00
MV Bus, 10.00 > kV > 1.00	VBus ≤ 90.00	95.00	0.00
LV Bus, kV ≤ 1.00	VBus ≤ 90.00	95.00	0.00

Figure 47—Motor-starting alert view option with critical and marginal alerts

14.3 Motor-starting plots and one-line diagram

The definition of typical motor-starting plots is shown in Table 7.

Table 7—Typical motor-starting plot parameters

Plot parameter	Definition
Slip	Motor slip with respect to applied frequency; for a VFD-controlled starting motor, this plot does not indicate motor speed if the applied frequency is not the rated value
Speed	Motor speed in percent of the synchronous speed for motor-rated frequency
Current (line)	VFD input current in percent of motor FLA
Current (terminal)	Motor terminal current in percent of motor FLA
$V_{terminal}$ (motor base)	Motor terminal voltage in percent of motor-rated kV
$V_{terminal}$ (bus base)	Motor terminal voltage in percent of VFD input terminal bus nominal kV
V_{bus}	VFD input terminal bus voltage in percent of bus nominal kV
Acceleration torque	Motor-acceleration torque in percent of motor-rated torque
Motor torque	Motor torque in percent of motor-rated torque
Load torque	Load torque in percent of motor-rated torque
kW (electrical)	VFD input real power in kW
kvar	VFD input reactive power in kvar
kW (mechanical)	Motor output power in kW
Frequency	VFD output frequency applied on motor
V/Hz	Motor terminal Volt/Hz in percent of motor-rated voltage and frequency

Table 8—Synchronous generators

Plot parameter	Definition
Power angle (relative)	Synchronous generator power (rotor) angle with respect to the reference machine in degrees equals the generator's absolute power (rotor) angle subtracting the reference machine's absolute power (rotor) angle; the relative power (rotor) angle is the indicator of the generator's stability
Power angle (absolute)	Synchronous generator absolute power (rotor) angle is solved from the generator swing equation in degrees
Speed	Synchronous generator speed in RPM
MW (mechanical)	Synchronous generator shaft mechanical power generation in MW
MW (electrical)	Synchronous generator electrical power generation in MW
Mvar	Synchronous generator reactive power in Mvar
Current	Synchronous generator terminal current in A
Efd	Synchronous generator field voltage in per unit
Ifd	Synchronous generator field current in per unit
Machine Z	Synchronous generator terminal impedance in percent on machine base

Table 9—Synchronous motors, MV (medium-voltage motors)

Plot parameter	Definition
Power angle (relative)	Synchronous motor power (rotor) angle with respect to the reference machine in degree equals the motor's absolute power (rotor) angle subtracting the reference machine's absolute power (rotor) angle; the relative power (rotor) angle is the indicator of the motor's stability
Power angle (absolute)	Synchronous motor absolute power (rotor) angle is solved from the motor swing equation in degree
Speed	Synchronous motor speed in RPM
MW (mechanical)	Synchronous motor mechanical power in MW
MW (electrical)	Synchronous motor electrical power in MW
Mvar	Synchronous motor reactive power in Mvar
Current	Synchronous motor terminal current in A
V_{bus}	Synchronous motor connected bus voltage in kV or percent of the bus nominal kV
$V_{terminal}$	Synchronous motor terminal voltage in kV or percent of bus nominal kV
Machine Z	Synchronous motor terminal impedance in percent on machine base

Table 10—Synchronous motors, LV (low-voltage motors)

Plot parameter	Definition
Power angle (relative)	Synchronous motor power (rotor) angle with respect to the reference machine in degree equals the motor's absolute power (rotor) angle subtracting the reference machine's absolute power (rotor) angle; the relative power (rotor) angle is the indicator of the motor's stability
Power angle (absolute)	Synchronous motor absolute power (rotor) angle is solved from the motor swing equation in degree
Speed	Synchronous motor speed in RPM
MW (mechanical)	Synchronous motor mechanical power in MW
MW (electrical)	Synchronous motor electrical power in MW
Mvar	Synchronous motor reactive power in Mvar
Current	Synchronous motor terminal current in A
V_{bus}	Synchronous motor connected bus voltage in kV or percent of the bus nominal kV
$V_{terminal}$	Synchronous motor terminal voltage in kV or percent of bus nominal kV
Machine Z	Synchronous motor terminal impedance in percent on machine base

Table 11—Induction machines, MV (medium-voltage machines)

Plot parameter	Definition
Slip	Induction machine slip in percent
Accel torque	Induction machine acceleration power in MW
MW (mechanical)	Induction machine mechanical power in MW
MW (electrical)e	Induction machine electrical power in MW
Mvar	Induction machine reactive power in Mvar
Current	Induction machine terminal current in A
V_{bus}	Induction machine connected bus voltage in kV or percent of the bus nominal kV
$V_{terminal}$	Induction machine terminal voltage in kV or percent of bus nominal kV
Machine Z	Induction machine terminal impedance in percent on machine base
V/Hz	Induction machine terminal voltage per Hz, where voltage is based on machine-connected bus nominal voltage (except for VFD-connected machines, which are based on machine-rated voltage) and frequency is based on system frequency (except for VFD-connected machines, which are based on VFD ac output frequency)

Table 12—Induction machines, LV (low-voltage machines)

Plot parameter	Definition
Slip	Induction machine slip in percent
Accel torque	Induction machine acceleration power in MW
MW (mechanical)	Induction machine mechanical power in MW
MW (electrical)	Induction machine electrical power in MW
Mvar	Induction machine reactive power in Mvar
Current	Induction machine terminal current in A
V_{bus}	Induction machine connected bus voltage in kV or percent of the bus nominal kV
$V_{terminal}$	Induction machine terminal voltage in kV or percent of bus nominal kV
Machine Z	Induction machine terminal impedance in percent on machine base
V/Hz	Induction machine terminal voltage per Hz, where voltage is based on machine-connected bus nominal voltage (except for VFD-connected machines, which are based on machine-rated voltage) and frequency is based on system frequency (except for VFD-connected machines, which are based on VFD ac output frequency)

Table 13—Buses

Plot parameter	Definition
Voltage angle	Bus voltage angle in degrees
Frequency	Bus frequency in percent of system frequency
MW	Bus real power loading in MW
Mvar	Bus reactive power loading in Mvar
V/Hz	Bus voltage per Hz in percent of bus nominal volt/system frequency in Hz
Voltage	Bus voltage magnitude in kV or percent of the bus nominal kV

Table 14—MOVs

Plot parameter	Definition
kvar	MOV reactive power loading in kvar
kW (electrical)	MOV electrical power loading in kW
Current	MOV current in A
V_{bus}	MOV connected bus voltage in kV or percent of the bus nominal kV
$V_{terminal}$	MOV terminal voltage in kV or percent of bus nominal kV

Table 15 —Branches

Plot parameter	Definition
MW (From)	Branch real power flow on the from side in MW
Mvar (From)	Branch reactive power flow on the from side in Mvar
I (From)	Branch current flow on the from side in A
MVA (From)	Branch apparent power flow on the from side in MVA
MW (To)	Branch real power flow on the to side in MW
Mvar (To)	Branch reactive power flow on the to side in Mvar
I (To)	Branch current flow on the to side in A
MVA (To)	Branch apparent power flow on the to side in MVA

Table 16 —Lumped loads

Plot parameter	Definition
MW	Lumped load electrical power loading in MW
Mvar	Lumped load reactive power loading in Mvar
Current	Lumped load current in A
Voltage	Lumped load-connected bus voltage in kV or percent of bus nominal kV

In addition to the tabulations and plots, the software is capable of displaying the calculation results on the one-line diagram. In some software, once a motor-starting calculation is finished, a time slider starts from time = 0 s to the final simulation time. As the pointer is moved along the ruler, the displayed results change accordingly. A sample is shown in Figure 48.

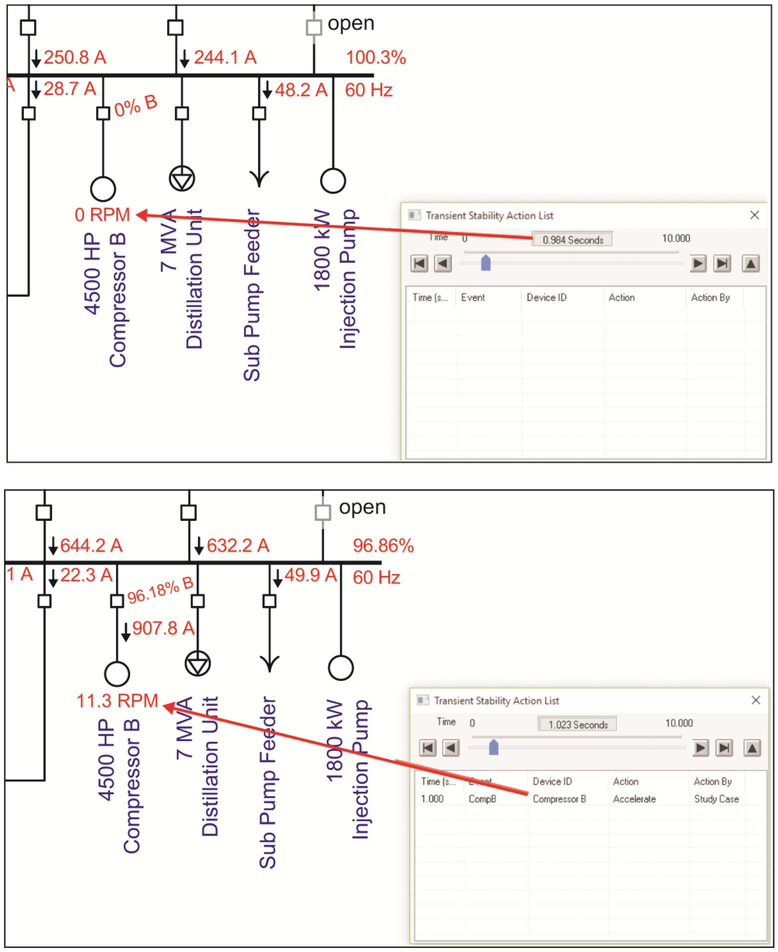


Figure 48—Typical one-line diagram results and action list varying as function of time at t = 0.984 s and t = 1.023 s

15. Features of analysis tools

15.1 Overview

Due to the complexity of most systems studied, computer-based tools (software) are often needed. The essential and optional features of any software are described in this clause.

15.2 Features required for most studies

Most studies will require the following features:

— Accelerate/stop multiple motors repeatedly at any time during a simulation

— Dynamically-modeled motors and loads

— Multiple motor starting using unlimited sequence of events

- Voltage impact of motor starting
- Compare the response from various types of motor starters
- Simulate load ramping of starting motor
- Vary generator/grid operating parameters
- Visualize results with alerts and warnings
- Simulate VFD frequency control motor starting
- Modify simulation time step to suit simulation needs
- Specify plot length by simulation time duration
- Include automatic protective device actions for 27, 59, 32, 50, etc.
- Motor torque and slip curves
- Typical and user-defined load models
- Transformer phase shift
- Simulate motor-starting devices including conventional starters and soft starters
  - Conventional reduced-voltage starting devices include autotransformer, capacitor, rotor/stator R or X, Y/Δ, and partial winding
  - Soft starter simulation including voltage, current, and torque-controlled starters
- Static load can be switched on and off repeatedly at any time during a simulation with predetermined loading
- Motor switching can be specified individually or by bus collection or by other grouping methods
- Multiple levels of automatic error checking
- Induction motor parameter estimation and tuning
  - Determines model parameters using motor running and starting conditions to generate circuit model and torque/speed curve
  - Automatic minimization techniques to locate best parameters to match manufacturer data
- Results and alerts
  - Graphical display of motor-starting time-varying simulation results
  - Auto-alert abnormal conditions with marginal or critical levels
  - Graphically display buses with marginal or critical voltage levels
  - Comprehensive motor-starting plots with operation details
  - Includes plotting multiple parameters on the same plot

15.3 Additional features

While not required by most studies, the following features may be useful:

- Automatic comparison of motor-starting results
- Automatically determine appropriate starter type for single motor start
- Transition loading of entire system

— Synchronous machine, full sub-transient flux model with saturation
— Simulate transformer LTCs/voltage regulators
— Modeling of starting, running loads, and auto-transfer of load
— Synchronous motor including field application
— Simulate MOVs with five operating stages; MOV can be started at any time during the simulation
— Induction/synchronous motor dynamic models
— Global or individual LTC time delays

15.4 Automatic comparison of motor-starting results

As we have seen, the combinations of motor-starting calculations performed in a typical industrial or commercial facility can be enormous and very time consuming. The engineer needs to spend adequate time identifying and filtering out cases that are inconsequential and/or redundant. Further time is required to view the output of these individual studies in order to determine the worst-case conditions in terms of voltage, acceleration time, and other criteria.

Motor-starting results can be compared and analyzed in a single tabular view. The engineer can compare the results of general information about a project or more specific information, such as the electrical load flow calculation results for buses, branches, loads, or sources. The purpose for the analyzer is to compare and analyze different tabulations, perhaps even from different projects, in order to determine the worst-case starting condition and longest/shortest acceleration times. The analyzer as shown in Figure 49, therefore, allows the user to select from a number of study reports or motor-starting cases for further analysis. The software then selects the relevant calculation results.

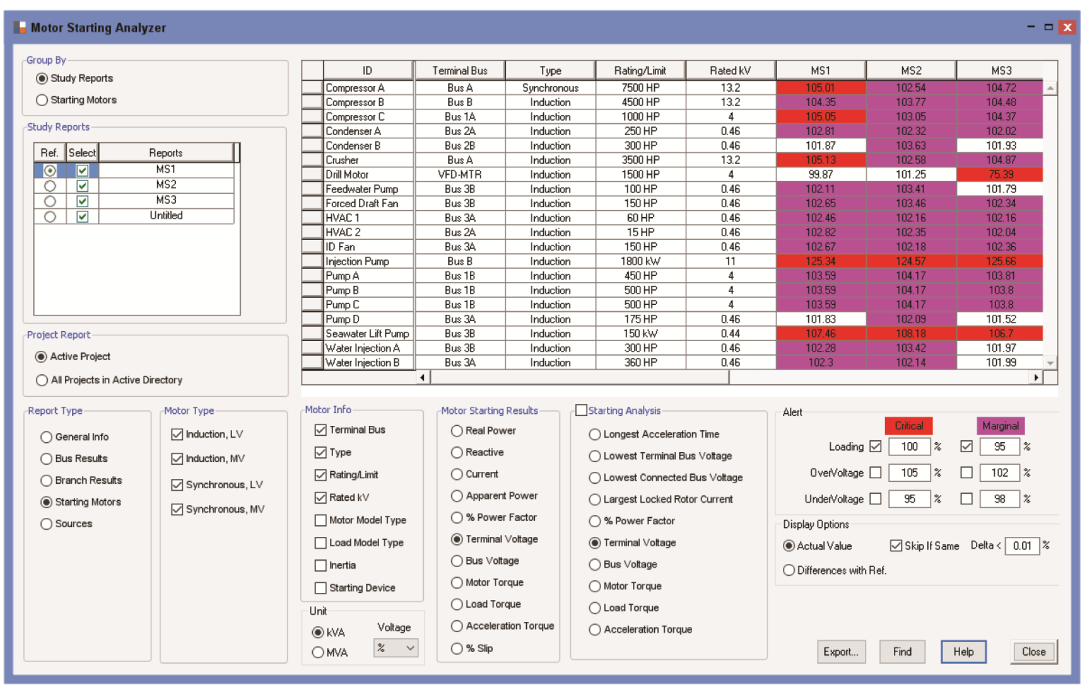


Figure 49—Motor-starting analyzer

A motor-starting analyzer allows the user to view and analyze starting motors based on multiple study scenarios. Starting analysis may be performed based on longest acceleration time, lowest terminal bus voltage, highest locked-rotor current, etc.

16. Illustration examples

16.1 Motor starting direct on-line versus motor starting with VFD

Figure 50 and Figure 51 show the motor-starting performances with fixed frequency control and variable frequency control compared (with respect to time) in each case with DOL start for the drill motor.

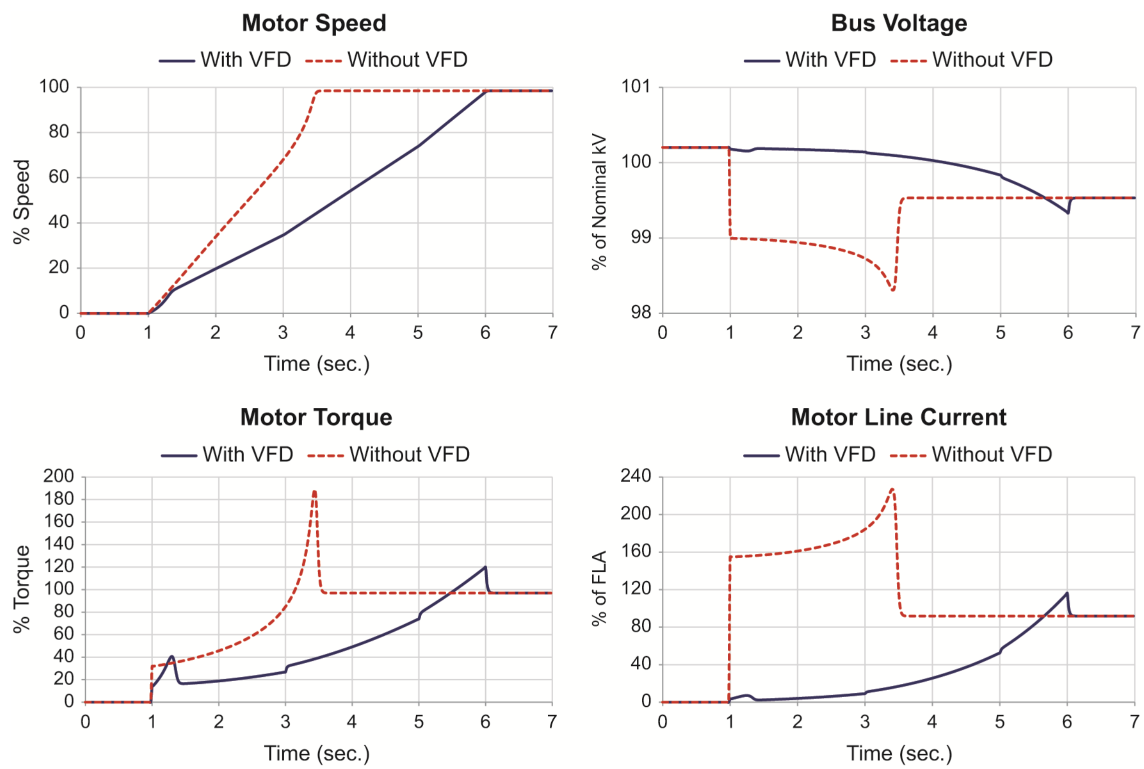


Figure 50—Motor-acceleration responses with fixed frequency VFD control and without VFD

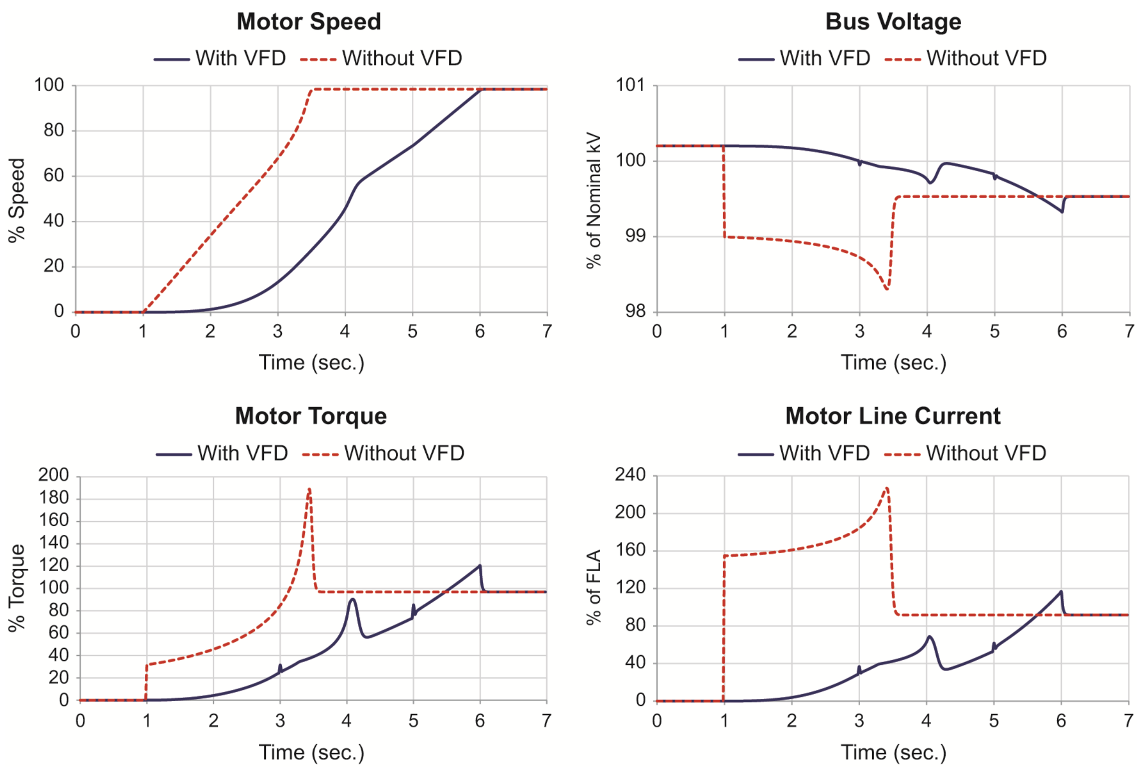


Figure 51—Motor-acceleration responses with variable frequency control VFD (variable V/Hz) and without VFD

16.2 Comparison of motor starting with common motor starters (voltage control, current limit, current control, torque control, etc.)

Table 17 summarizes the starting voltage, current, and torque developed due to various starting methods. Examples with typical starting curves and starting curves for compressor B with H = 1.4 and load torque = $a \times k^3$ are shown. Figure 52 through Figure 59 show the various motor-starting methods.

Table 17—Motor starter comparisons[a]

Starting method	Percent voltage	Percent current	Percent torque
Direct on-line	100	100	100
Resistor/reactor (80% tap)	80	80	64
Resistor/reactor (65% tap)	65	65	42
Resistor/reactor (50% tap)	50	50	25
Autotransformer (80% tap)	80	64	64
Autotransformer (65% tap)	65	42	42
Autotransformer (50% tap)	50	25	25
Wye–delta	100	33	33
Partial winding	100	70	50

[a] Values are based on percent of normal (full voltage) at motor.

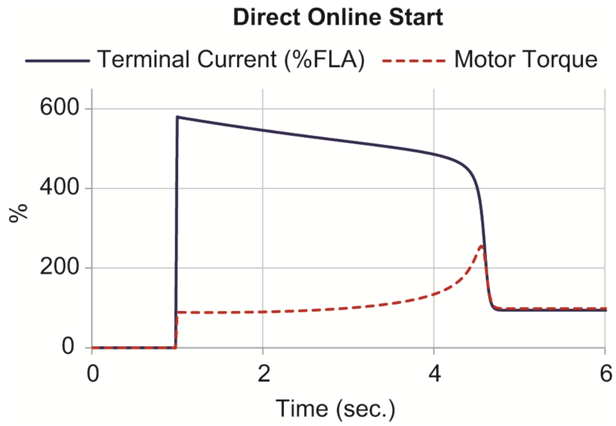


Figure 52—Direct on-line start

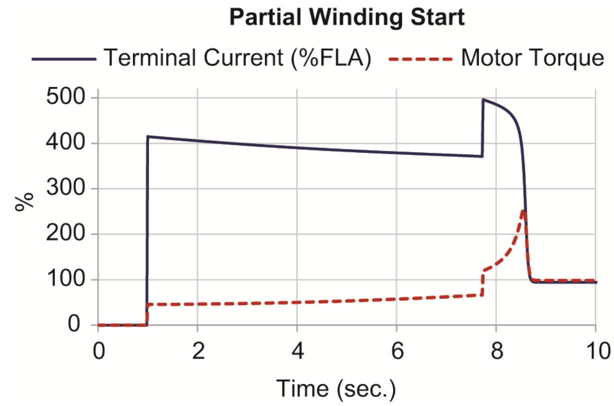


Figure 53—Partial winding start

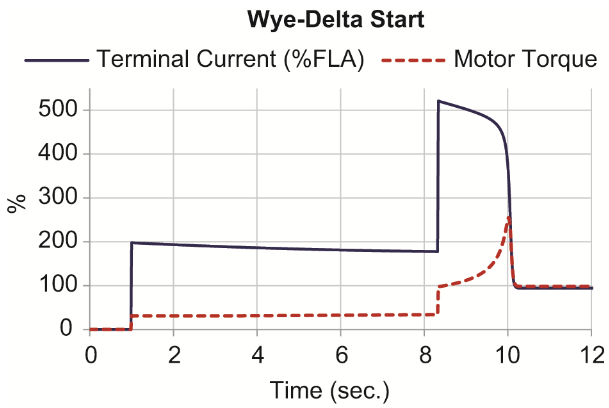


Figure 54—Wye–delta start

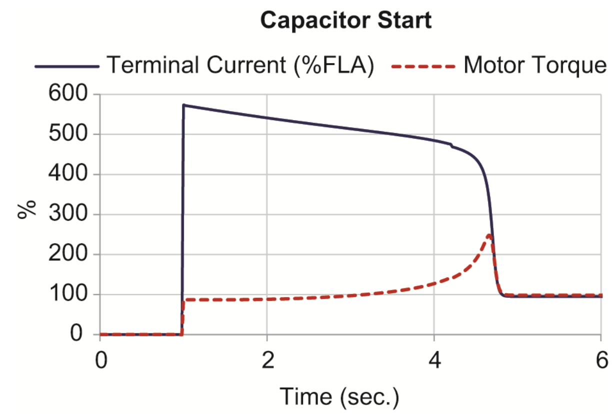


Figure 55—Capacitor start

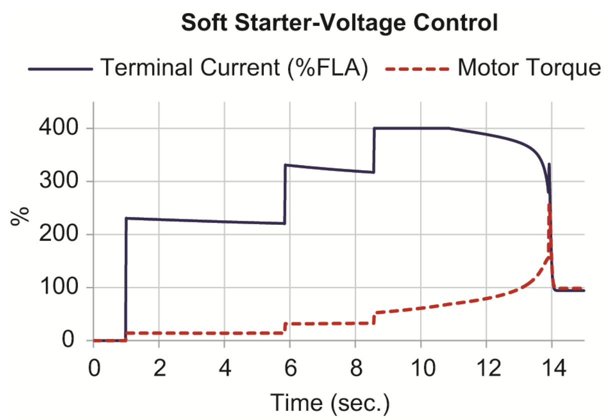


Figure 56—Soft starter: voltage control

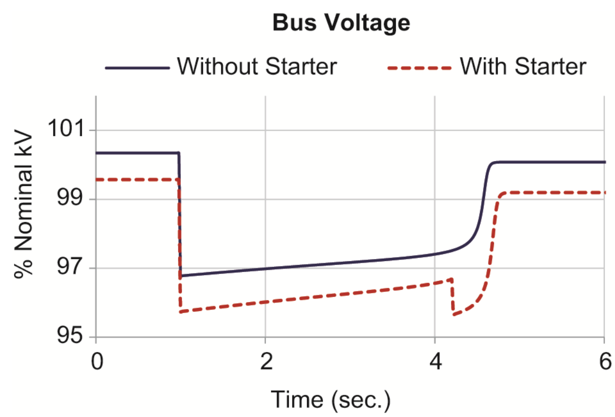


Figure 57—Terminal voltage: soft start versus direct on-line

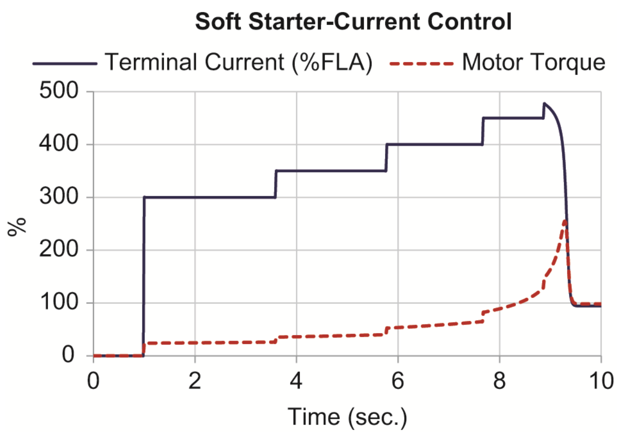


Figure 58—Soft starter: current control

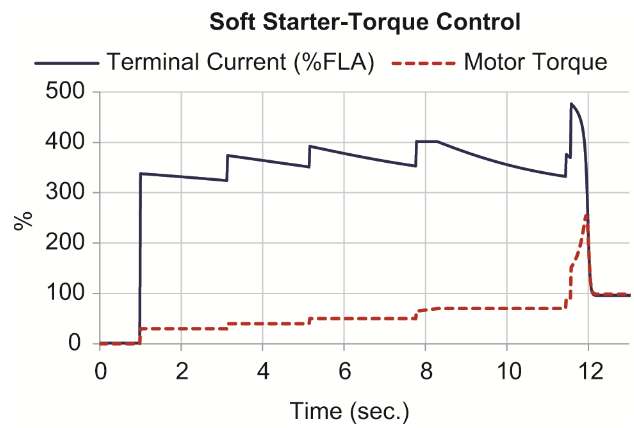


Figure 59—Soft starter: torque control

16.3 Motor reacceleration

It may be necessary to analyze the response of the system and the motor in instances where power is temporarily lost on a bus due to a transient disturbance or during bus transfer. This type of disturbance can temporarily disconnect the power to the motor. Ideally, the rotating system inertia of the motor (rotor, coupling gear, and driven equipment) will let it rotate indefinitely. But due to friction and windage losses and connected load-torque requirements, the motor speed will start reducing. The rate of speed reduction depends on the magnitude of friction and windage losses, the connected load torque, and the inertia of the machine. The higher the inertia, the longer time for the motor to coast to a complete stop. Higher friction and windage losses will cause the motor to coast to complete stop at a faster rate.

Reacceleration is possible on motors starting directly across the line once the magnetic flux has decayed; however, if there are motors with VFDs then such reacceleration may only be possible if the VFD supports a “flying restart” mode. A typical motor reacceleration profile is shown in Figure 60.

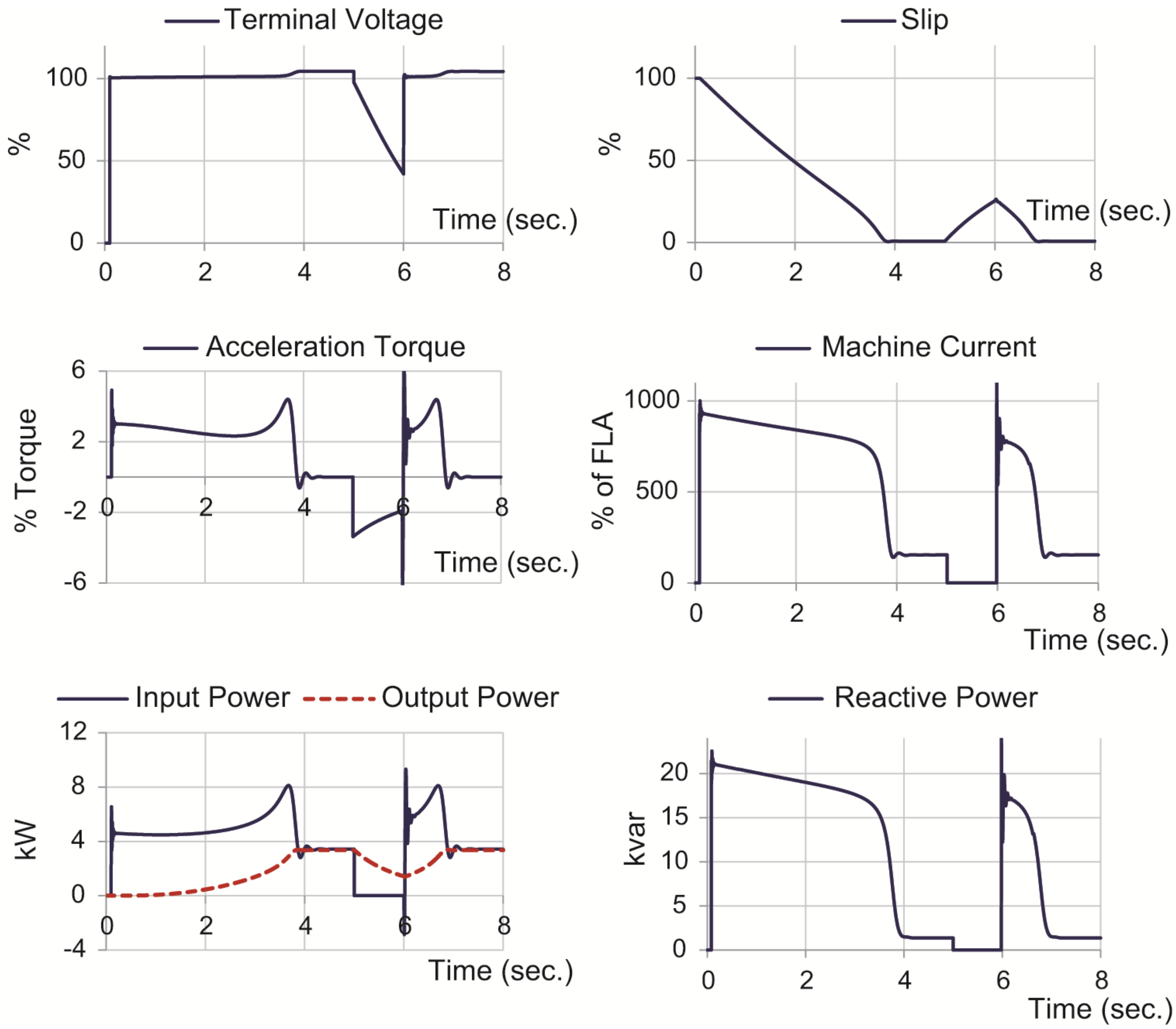


Figure 60—Typical motor reacceleration profile with power supply temporarily disconnected for 1 s

Annex A

(informative)

Bibliography

Bibliographical references are resources that provide additional or helpful material but do not need to be understood or used to implement this standard. Reference to these resources is made for informational use only.

[B1] Alger, P. L., *Induction Machines, Their Behavior and Uses,* New York: Gordon and Breach Science Publishers, 1970.

[B2] Beaty, H. W, and J. L. Kirtley, *Electric Motor Handbook,* New York: McGraw-Hill Professional, 1998.

[B3] Beeman, D., Ed., *Industrial Power Systems Handbook*, New York: McGraw-Hill, 1955.

[B4] Clarage, "Fan Engineering," http://www.clarage.com/resources.

[B5] Croft, T., C. Care, and J. Watt, *American Electrician's Handbook,* New York: McGraw-Hill, 1970.

[B6] CEDengineering.com, "Introduction to Motor Starting Analysis," course no. E05-008.

[B7] CEDengineering.com, "Understanding Motor Nameplate Information: NEMA vs. IEC Standards," course no. E03-009.

[B8] Clark, J. "Demystifying Metric: NEMA vs. IEC Motors," ABB, Inc.

[B9] Diamond, J. H., "Stall Time, Acceleration Time, Frequency of Starting: The Myths and the Facts," *IEEE Transactions on Industry Applications,* vol. IAS 29, no. 1, pp. 42–51, 1993.[6, 7]

[B10] Donner, G. L., B. Subler, and S. Evon, "A Motor Primer. (Part 1)," *Industry Applications Society 46th Annual Petroleum and Chemical Technical Conference,* pp. 293–307, San Diego, CA, 13–15 Sept. 1999.

[B11] ETAP, *ETAP Power Systems Software User Guide,* Irvine, CA: ETAP/Operation Technology, 2015.

[B12] ETAP, "Motor Acceleration," Irvine, CA: ETAP/Operation Technology.[8]

[B13] ETAP, "Motor Starting Analysis Software for Libraries and Modeling," http://etap.com/motor-starting/motor-starting-libraries-modeling.htm Irvine, CA: ETAP/Operation Technology.

[B14] ETAP, "Voltage Drop Calculation Software/Load Flow Analysis," Irvine, CA: ETAP/Operation Technology.[9]

[B15] Fitzgerald, A., C. Kingsley, and A. Kusko, *Electric Machinery*, New York: McGraw-Hill, 1971.

[B16] Harbaugh, J., and L. Ponsting, "How to Design a Capacitor Starting System for Large Induction and Synchronous Motors," *IEEE Industry Applications Society Annual Meeting,* Atlanta, GA, 28 Sept.–2 Oct. 1975.

[B17] IEC 60034 (Series), Rotating Electrical Machines.[10]

[6] The IEEE standards or products referred to in Annex A are trademarks owned by The Institute of Electrical and Electronics Engineers, Incorporated.
[7] IEEE publications are available from The Institute of Electrical and Electronics Engineers (http://standards.ieee.org/).
[8] https://etap.com/docs/default-source/whats-new/etap-18-1-new-features-brochure-v1.pdf?sfvrsn=64.
[9] https://etap.com/docs/default-source/faqs-tutorials/load-flow-analysis.pdf?sfvrsn=10.

[B18] IEEE Power Generation Committee, "Computer Representation of Excitation Systems," *IEEE Transactions on Power Apparatus and Systems,* vol. 1, no. 6, pp. 1460–1464, June 1968.

[B19] IEEE Std 112™-1996, IEEE Standard Test Procedure for Polyphase Induction Motors and Generators.

[B20] IEEE Std 141™-1993, IEEE Recommended Practice for Electric Power Distribution for Industrial Plants (*IEEE Red Book*™).

[B21] IEEE Std 242™-2001, IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems (*IEEE Buff Book*™).

[B22] IEEE Std 666™-2007, IEEE Design Guide for Electric Power Service Systems for Generating Stations.

[B23] IEEE Std 841™-2001, IEEE Standard for Petroleum and Chemical Industry—Severe Duty Totally Enclosed Fan-Cooled (TEFC) Squirrel-Cage Induction Motors — up to and Including 370 kW (500 HP).

[B24] IEEE Std 1255™, IEEE Guide for the Evaluation of Torque Pulsations During Starting of Synchronous Motors.

[B25] IEEE Std 3001.11™-2017, IEEE Recommended Practice for Application of Controllers and Automation to Industrial and Commercial Power Systems.

[B26] IEEE Std 3004.8™-2016, IEEE Recommended Practice for Motor Protection in Industrial and Commercial Power Systems.

[B27] IEEE Std C37.010™-1999, IEEE Application Guide for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.

[B28] IEEE Std C37.96™-2012, IEEE Guide for AC Motor Protection.

[B29] Khan, S., *Industrial Power Systems*, New York: CRC Press, 2007.

[B30] Kimbark, E., *Power System Stability: Synchronous Machines*, New York: Dover Publications, 1956.

[B31] Manning, L., *Electrical Circuits*, New York: McGraw-Hill, 1966.

[B32] Mistry, R., W. Finley, and T. Gaerke, "Comparison of IEC and NEMA Requirements to Ensure Proper Specification and Design of Induction Motors and Generators for Global Use," *2017 Petroleum and Chemical Industry Technical Conference (PCIC)* pp. 35–44, Alberta, Canada, 18–20 Sept. 2017.

[B33] NEMA ICS 1-2000, Requirements for Industrial Control and Systems.[11]

[B34] NEMA ICS 2-2000, Industrial Control Devices, Controllers and Assemblies.

[B35] NEMA ICS 4-2015, Terminal Blocks for Industrial Control and Systems.

[B36] NEMA ICS 6-1993, Enclosures for Industrial Control and Systems.

[B37] NEMA MG 1-2016, Motors and Generators.

[B38] NEMA MG 2-2014, Safety Standard and Guide for Selection, Installation, and Use of Electric Motors and Generators.

[B39] NFPA 70, National Electrical Code® (NEC®)[12, 13]

[B40] Neuenswander, J. R., *Modern Power Systems*, Scranton, PA: International Text Book Company, 1971.

---

[10] IEC publications are available from the International Electrotechnical Commission (http://www.iec.ch) and the American National Standards Institute (http://www.ansi.org/).
[11] NEMA publications are available from the National Electrical Manufacturers Association (http://www.nema.org/).
[12] NFPA publications are published by the National Fire Protection Association (http:// www.nfpa.org/).
[13] The NEC is published by the National Fire Protection Association (http://www.nfpa.org/). Copies are also available from The Institute of Electrical and Electronics Engineers (http://standards.ieee.org/).

[B41] Nevelsteen, J., and H. Aragon, "Starting of Large Motors—Methods and Economics," *IEEE Transactions on Industry Applications,* vol. 25, no. 6, pp. 1012–1018, Nov./Dec. 1989.

[B42] Peterson, H., *Transients in Power Systems,* New York: Dover Publications, 1951.

[B43] Prabhakara, F. S., R. L. Smith, Jr., and R. P. Stratford, *Industrial and Commercial Power Systems Handbook*, New York: McGraw-Hill, 1995.

[B44] Stagg, G. W., and A. H. El-Abiad, *Computer Methods in Power System Analysis*, New York: McGraw-Hill, 1971.

[B45] UL 347, Medium-Voltage AC Contactors, Controllers, and Control Centers.[14]

[B46] UL 60947-4-1, Low-Voltage Switchgear and Controlgear—Part 4-1: Contactors and Motor-Starters—Electromechanical Contactors and Motor-Starters.

[B47] Weidmer, R., and R. Sells, *Elementary Classical Physics*, 2 vols., Boston: Allyn and Bacon, 1965.

[B48] WEG, Electric motor selection," Jaraguá do Sul, Brazil.[15]

[B49] Westinghouse, *Electrical Transmission and Distribution Reference Book,* East Pittsburgh, PA: Westinghouse Electric, 1944.

[B50] Zimmerman, J. A., and W. O. Richardson, "Motor Starting with Capacitors," *IEEE Transactions on Industry and General Applications,* vol. 5, no. 6, pp. 759–765, Nov. 1969.

[14] UL publications are available from Underwriters Laboratories (http://www.ul.com/).
[15] http://ecatalog.weg.net/TEC_CAT/tech_motor_sel_web.asp?cd_produto=30&CD_CATEGORIA_PRODUTO=5&cd_mercado=000E&cd_idioma_cat=EN&cd_empresa=110

Annex B

(normative)

Comparison between NEMA and IEC motor standards

Comparison	NEMA	IEC
Frame relationships	Uses a NEMA-specific numerical code to specify the physical frame dimensions.	Uses an IEC-specific numerical code to specify the physical frame dimensions.
Enclosure	Designations indicate protection provided by a motor's enclosure. Designations are in words, such as "Open Drip Proof" or "Totally Enclosed Fan Cooled."	Has designations (like NEMA) indicating the protection provided by a motor's enclosure. IEC uses a two-digit "Index of Protection" code to refer to a set of definitions found in IEC standards that establish expected performance characteristics of enclosures.
Cooling	Designation under "details of protection" consists of the letter "IP" followed by two characteristic numerals. Refer to NEMA MG1 for more details.	Consists of the letters "IC" followed by numbers and letters representing the circuit arrangements. There is an individual code for most types of cooling methods, from small fan-cooled motors to large liquid-cooled motors.
Duty cycles	Three ratings: continuous, intermittent, or special duty (typically expressed in minutes).	Eight ratings: S1 to S8.
Design types	Design codes similar to IEC, but with different letters. Most common industrial motor is Design B.	Design codes similar to NEMA, but with different letters. Most common industrial motor is Design N. Design rating code describes a motor's speed versus torque characteristics.
Insulation designations	Classification system for winding insulation based on the highest temperature the material can withstand continuously without degrading or reducing motor life. Service factor of 1.0, 1.15, or higher.	No "Service Factor" rating definition. IEC and NEMA 1.0 service factor ratings are nearly identical.
Output power	Horsepower (HP) 1 HP = 745.7 W = 0.7457 kW	Power (kW), temperature rise, ambient temperature, and altitude ratings are defined via the kW output rating and if any increase in kW output is required, the next size motor will be selected.
Efficiency	100%, 75%, and 50% loading	100% and 75% loading
Frame relationships	Uses a NEMA-specific numerical code to specify the physical frame dimensions.	Uses an IEC-specific numerical code to specify the physical frame dimensions.

Consensus

WE BUILD IT.

IEEE
standards.ieee.org
Phone: +1 732 981 0060 Fax: +1 732 562 1571